The Internet of (Important) Things

Thomas WATTEYNE

Mémoire d'Habilitation à Diriger des Recherches

Sorbonne Université – Inria

Presented on 7 May 2019.

Jury:

Prof. Benoit Geller	ENSTA ParisTech, Palaiseau, France	Reviewer
Prof. Jean-Marie Gorce	INSA Lyon, Villeurbanne, France	Reviewer
Dr. Nathalie Mitton	Inria, Lille, France	Reviewer
Dr. Fabrice Theoleyre	Université de Strasbourg, France	Examiner
Dr. Marcelo Dias de Amorim	Sorbonne University, Paris, France	Examiner
Prof. Branko Kerkez	University of Michigan, MI, USA	Examiner

This version of the manuscript was compiled on May 21, 2019.

Acknowledgements

I've had the immense privilege, from the start of my research career, to be working with some of the most brilliant and inspiring people in the field. These have been both people who have mentored me, or people I have mentored. All have allowed me to progress in this field, either understand a technical detail better, or broaden my scope and pointing me at something I hadn't considered before.

I am too afraid of forgetting names by thanking specific people; I therefore will not cite specific names, although I'm sure you will recognize yourself.

There is however one person I would like to cite, and who has had a profound impact of every aspect of my research, Kris Pister. Since 2009, he has been providing me with continuous guidance and support. There is not a single idea or direction I haven't been able to talk to him about, and for which he hasn't giving me clever and constructive insights. His role in my research has been so transformative, it is hard for me to imagine what I would be working on hadn't I met him.

I would also like to thank the members of my jury, and in particular the reviewers. It is an honor for me to be able to present my work to you.

Contents

Part I

Activities Report

0.1 Positions Held

- *Jan. 2018 – Nov. 2020.* Advanced Research Position (ARP).
  Inria, Paris, EVA team.
- *Jan. 2015 – Dec. 2017.* Starting Research Position (SRP).
  Inria, Paris, EVA team.
- *Dec. 2011 – today.* Senior Networking Design Engineer.
  Linear Technology, Silicon Valley, USA.
- *Dec. 2010 – Dec. 2011.* Senior Networking Design Engineer.
  Dust Networks, Silicon Valley, USA.
- *Feb. 2009 – Dec. 2010.* Postdoctoral Research Lead.
  University of California, Berkeley, USA.
- *Oct. 2008 – Dec. 2008.* Research Engineer.
  INSA Lyon, CITI Lab.
- *Oct. 2005 – Sep. 2008.* Research Engineer / PhD student (CIFRE).
  Orange Labs, Meylan, France.
- *Sep. 2005 – Jun. 2008.* Teaching assistant (vacataire).
  INSA Lyon, Telecommunications Department.

0.2 Honors and Awards

- **Finalist, best paper award** at the Global IoT Summit 2018, for paper *Why Channel Hopping Makes Sense, even with IEEE802.15.4 OFDM at 2.4 GHz.*
- Identified as **"Key Innovator" by the European Commission**'s Innovation Radar for category "commitment" for the innovation "*Online platform of testing tools for the Internet of Things*", 2018.
- *SmartMesh IP* awarded "**Internet of Things Product of the Year**" at the Annual Creativity in Electronics (ACE) Awards, 6 December 2017. *(Note: although this is not a personal award, all approx. 12 of us in the core SmartMesh IP team are very proud)*
- *SolSystem* selected as one of the 10 **testbeds at the IoT Solutions World Congress**, Barcelona, Spain, 3-5 October 2017.
- Recipient of the **France-Berkeley Fund award** for the project "*SHRIMP: Smart Harbor Implementation*" with Prof Steven Glaser, August 2016.

- **Runner up IEEE SECON 2016 Best Demo Award** with "*A Demo of the PEACH IoT-based Frost Event Prediction System for Precision Agriculture*" with Keoma Brun-Laguna, Ana Laura Diedrichs, Javier Emilio Chaar, Diego Dujovne, Juan Carlos Taffernaberry, Gustavo Mercado, London, UK, 28 June 2016.

- Recipient **Google IoT Technology Research Award** on "*6TiSCH and WiFi coexistence with OpenWSN*", together with Remy Leone, March 2016.

- **EWSN dependability competition 4th place** with project "*Reliability through Time-Slotted Channel Hopping and Flooding-based Routing*" with Pedro Henrique Gomes, Pradipta Gosh, Bhaskar Krishnamachari and Tengfei Chang, 16 February 2016.

- **WINNER IPSO CHALLENGE 2015 People's Choice Award** with project "*HeadsUp! : monitoring the post-surgery position of retinal detachment patients*" together Brett Warneke, 3 December 2015.

- **IPSO CHALLENGE 2015 Third Place** with project "*uPnP: Harnessing the Power of IPv6 for Ultra Low Power, Zero-configuration IoT Networks*" together with Danny Hughes, Nelson Matthys, Wilfried Daniels and Fan Yang, 2 December 2015.

- Elevated to **IEEE Senior Member**, August 2015.

- **Distinguished Publication Award** from the *Magnetics Society of Japan* for chapter "*6TiSCH Wireless Industrial Networks: Determinism Meets IPv6*" in book "*Internet of Things: Challenges and Opportunities*", 2014.

- Project *OpenWSN* recipient **Outstanding Research** award by the Berkeley Sensor & Actuation Center (BSAC) during Industrial Advisory Board (IAB) poster session at **UC Berkeley** in 2010.

- **Best presentation award** for "*1-hopMAC: An Energy-Efficient MAC Protocol for Avoiding 1-hop Neighborhood Knowledge*" at Summer School SenZations, Novi Sad, Serbia, August 2006.

- MsC obtained with **greatest honors**, 2005.

- MEng obtained with **honors**, 2005.

0.3 Supervision of Research Activities

For an up-to-date list of people I have advised, see `https://twatteyne.wordpress.com/advising/`. For an up-to-date list of members of the Inria-

EVA project team, see `https://team.inria.fr/eva/` . I detail the contributions of the most recent people I have advised.

PhD Students

1. **Keoma Brun-Laguna**

Keoma Brun-Laguna is the PhD student with whom I've worked the most on the SaveThePeaches, SnowHow and SmartMarina deployments. That activity has allowed him to master the sensor-to-cloud solution. Dr. Keoma Brun-Laguna is one of the co-founders of our startup, Falco.

   - PhD student
     - Co-advised by Dr. Pascale Minet.
     - I evaluate my portion of his advising at **90%**.
   - topic: Deterministic Networking for the Industrial IoT
   - January 2016 – December 2018

2. **Jonathan Munoz**

Jonathan Munoz is finishing his PhD. He has done a thorough applicability study of long-range technologies (in particular, IEEE802.15.4g) for mesh networking solutions, and is currently evaluating the performance of that solution in OpenWSN, using OpenMote devices. He is the one who coordinated the deployment of the OpenTestbed at Inria-Paris, see Fig. 5.1. I expect long-range mesh networks to revolutionize the space in the next 3-4 years.

   - PhD student
     - Co-advised by Dr. Paul Muhlethaler.
     - I evaluate my portion of his advising at **95%**.
   - topic: km-scale Industrial Networking
   - January 2016 – March 2019

3. **Mina Rady**

Mina just started his PhD in January 2019, under a CIFRE agreement with Orange Labs. He is continuing the work of Jonathan Munoz, specifically on creating a solution which combines IEEE802.15.4g long-range mesh networking with LoRa (a popular long-range star topology solution).

   - PhD Student, under a CIFRE agreement with Orange Labs

  - Co-advised by Paul Muhlethaler from Inria-EVA, Dominique Barthel from Orange Labs, Quentin Lampin from Orange Labs.
  - I evaluate my portion of his advising at **30%**.
- topic: Long-range IoT Heterogeneous Mesh Networks
- January 2019 – December 2021

4. **Tengfei Chang**

   Tengfei was a PhD student at the University of Science and Technology, Beijing. He was a visitor in the Pister lab at UC Berkeley (February – May 2014), during which time I was his main advisor. We kept working together on the OpenWSN project since then. I hired Tengfei at Inria in November 2015 to work on the OpenWSN project while he was finalizing his PhD. He eventually defended and got his PhD in late 2017. While I'm NOT his main advisor, I evaluate my portion of his advising at **20%**.

   - PhD Student, University of Science and Technology, Beijing
     - Advised by Prof. Qin Wang.
     - I evaluate my portion of his advising at **20%**.
   - topic: Time Synchronized Channel Hopping
   - 2013 – 2017

Master Student

1. **Moritz Hoffmann**

   Moritz Hoffmann spent 4 months working with me in the Dust Network startup as part of his Masters studies at ETH Zurich. Together, we worked on the open-source `http://www.dustcloud.org` community, which is now the reference implementation to interface to SmartMesh products.

   - Master student from ETH Zurich, at Dust Networks (USA)
   - topic: Implementing the SmartMesh IP Ecosystem
   - September – December 2012

Postdocs

1. **Dr Malisa Vucinic**

   We worked together with Malisa Vucinic when he spent 4 months at UC Berkeley in 2015, where he implemented link-layer security in OpenWSN. I hired him as a postdoc on the H2020 ARMOUR project. Malisa has been developing the concept of object security in the IoT, in particular for the secure joining process. In that aspect, object security offers the same services as for example dTLS, but for a fraction of the overhead. Object security is now the solution of the 6TiSCH secure join procedure, and the object of an IETF working group. Dr Malisa Vucinic joined the Inria-EVA team under an SRP contract in November 2018.

   - Postdoctoral researcher, at Inria
   - topic: Security for the IoT, part of the H2020 ARMOUR project
   - October 2016 - September 2017

2. **Dr Tengfei Chang**

   Dr Tengfei Chang has been a pilar of the OpenWSN community, and is the "behind-the-scenes" person that has been implementing the specifications defined in the 6TiSCH standardization group. His technical work has enabled us to organize the 5 6TiSCH interop events. The OpenWSN implementation is used as "golden image" for 6TiSCH by ETSI.

   - Postdoctoral Research Engineer, at Inria
   - topic: open-source OpenWSN implementation and community manager
   - 2016–2020

3. **Dr Keoma Brun-Laguna**

   Dr Keoma Brun-Laguna is technical lead of the Falco startup, a spin off of the team. He is my former PhD student, see above.

   - Postdoctoral Research Engineer, at Inria
   - topic: Associate Director, Systems and Networking, Falco
   - January – December 2019

4. **Dr Ziran Zhang**

   Dr Ziran Zhang spent 16 months in the team after graduating from UC Berkeley, to work on the SmartMarina research project, which eventually turned into the Falco startup.

   - Postdoctoral Research Lead, Inria-SiliconValley fellow

- topic: Infrastructure Monitoring in a Smart Marina Environment
- January 2017 – April 2018

5. **Dr Remy Leone**

   Dr Remy Leone worked in the team on the H2020 F-Interop project which has revolutionized the way interoperability testing is being conducted for the IoT. The solution he has developed is now in production and used by all F-Interop users, which includes 2 IETF working groups.

   - Postdoctoral Research Engineer, at Inria
   - topic: Redefining Interoperability Testing for the Internet of Things
   - 2016–2018

6. **Dr Nicola Accettura**

   - Postdoctoral Researcher, at UC Berkeley *(co-advised by Prof. Kris Pister from UC Berkeley, I evaluated by portion of his advising at 60%)*
   - topic: OpenWSN
   - April 2014 – August 2015

Engineers

1. **Trifun Savic**

   Trifun Savic joined Inria in February 2019 on the GeoBot project (`https://geobot.fr/`), where he is designing an underground localization solution to be able to localize and map gas pipes to avoid accidents.

   - Research Engineer, at Inria
   - topic: Subterranean localization, Geobot project
   - February 2019 – October 2020

2. **Yasuyuki Tanaka**

   Yasuyuki Tanaka has been building the 6TiSCH simulator (`https://bitbucket.org/6tisch/simulator`) used by the 6TiSCH community to evaluate the performance of the standards. He is currently developing a new 6TiSCH Scheduling Function (SF), which he is evaluating using his simulator.

   - Research Engineer, at Inria *(co-advised by Dr. Pascale Minet; I evaluate by portion of his advising at 40%)*
   - topic: 6TiSCH Distributed Scheduling and simulation
   - January 2018 – December 2019

Undergraduate Student researcher

1. **Felipe Moran**

   Felipe Moran built a solution to monitor the energy consumption of a low-power wireless device, which we are using at the Inria-EVA team.

   - MEng intern from ENSTA ParisTech and EDF fellow, at Inria
   - topic: mote feeding habits, SmartMesh IP
   - 1 September 2017 – 31 August 2018

2. **Fabian Rincon Vija**

   Fabian Rincon Vija did the technical work in creating and deploying the OpenTestbed at Inria-Paris.

   - MEng intern from ENSTA ParisTech, at Inria
   - topic: Extension of F-Interop to IEEE802.15.4 sub-GHz
   - 14 May – 31 August 2018

3. **Marcelo Augusto Ferreira**

   - MEng intern from ENSTA ParisTech, at Inria
   - topic: Measuring Energy Consumption in F-Interop
   - 1 May – 31 August 2018

4. **Constanza Perez Garcia**

   - Undergraduate student researcher from Universidad Diego Portales *(co-advised by Prof. Diego Dujovne from UDP)*
   - topic: Mercator: Dense Wireless Connectivity Datasets for the IoT
   - June – September 2014

5. **Pedro Issa Helou**

   - Undergraduate student researcher from Universidade de Brasilia (Brasil) *(co-advised by Dr. Oana Iova during his internship at the ICube laboratory in Strasbourg, France)*
   - topic: Running OpenWSN on the IoT–LAB Testbed
   - May – August 2014

6. **Oleksiy Budilovsky**

   - post-graduate researcher, at UC Berkeley
   - topic: Ring of Things: the First Social Network for Things

- February – November 2014

7. **Ahmad Dehwah**
    - Visiting PhD student from the King Abdullah University of Science and Technology, at UC Berkeley *(co-advised by Xavi Vilajosana from UOC)*
    - topic: Implementing the RPL Routing Protocol in OpenWSN
    - May – August 2011

8. **Edmund Ye**
    - Undergraduate student researcher, at UC Berkeley *(co-advised by Fabien Chraim from UC Berkeley)*
    - topic: Implementing the IEEE802.15.4e TSCH Standard in OpenWSN
    - February – July 2011

9. **Boyang Zhang**
    - Undergraduate student researcher, at UC Berkeley
    - topic: Building a 16–channel Sniffer for Channel Hopping IEEE802.15.4 MAC Protocols
    - October 2009 – March 2010

10. **Hilfi Alkaff**
    - Undergraduate student researcher, at UC Berkeley
    - topic: Implementing Timeslotted Channel Hopping in Contiki
    - October 2009 – March 2010

11. **Nahira Sarmicanic**
    - Undergraduate student researcher, at UC Berkeley
    - topic: Video Transmission in TSCH Networks
    - October 2009 – March 2010

12. **Leonid Keselman**
    - Undergraduate student researcher, at UC Berkeley *(co-advised by Dr. Anita Flynn from UC Berkeley)*
    - topic: Porting OpenWSN onto the GINA Platform
    - October 2009 – March 2010

13. **Christopher A. Jian**

- Undergraduate student researcher, at UC Berkeley *(co-advised by Ankur Mehta from UC Berkeley)*
- topic: Model Rocket–Based Mote Deployment
- May – August 2009

14. **Guilhem Tesseyre**
    - MEng student (non-scientific project), at INSA Lyon
    - topic: Music Today: between Diversity and Mass-Consumption (non-scientific project)
    - June 2008

15. **Clément Burin des Roziers**

    Clément Burin des Roziers helped with conducting experiments at the end of my PhD, and is now a lead engineer at HiKoB, an Inria startup (now TagMaster/SEQUANTA).

    - PFE "Projet de Fin d'Etudes" MEng student researcher, at France Telecom R&D Grenoble
    - topic: Setting up a Large Scale Wireless Sensor Network Experimentation
    - October 2007 – February 2008

16. **Marwen Bayar**
    - MEng student researcher, at INSA Lyon *(co-advised by Dr. Isabelle Auge-Blum)*
    - topic: Simulating Cross-layer Protocols for Wireless Sensor Networks using GTSNetS
    - October 2007 – February 2008

17. **Yoann Spadavecchia** and **Remi Favre**
    - MEng student researcher, at INSA Lyon *(co-advised by Dr. Isabelle Auge-Blum)*
    - topic: Implementing a Realistic Propagation Model on the GTSNetS Simulator
    - November 2006 – February 2007

18. **Wassim Mazraani**
    - MEng student researcher, at INSA Lyon *(co-advised by Dr. Isabelle Auge-Blum)*
    - topic: Implementing the 1-hopMAC Protocol on the GTSNetS Simulator

- November 2006 – February 2007

19. **Michaël Gauthier**
    - PFE "Projet de Fin d'Etudes" MEng student researcher, at France Telecom R&D Grenoble
    - topic: Wireless Sensor Network Communication Protocol Implementation on Real Motes. Michael's final demonstration was to replicate the 2001 Twenty Nine Palms demo by Prof. Kris Pister at Berkeley. Check out the (very cool) results.
    - October 2006 – March 2007

20. **Balazs Tirpak**
    - Undergraduate student researcher from the Budapest Tech Polytechnical Institution visiting the CITI Lab, at INSA Lyon
    - topic: Implementing Self-Organization Protocols for Wireless Sensor Networks on the GTSNetS simulator
    - October 2006 – March 2007

21. **Mickaël Beaupoil**
    - MEng student (non-scientific project), at INSA Lyon
    - topic: Blood Donors: How to Convince People (non-scientific project)
    - June 2006

22. **Guillaume Vaquero** and **Loic Michel**
    - MEng student researcher, at INSA Lyon *(co-advised by Dr. Isabelle Auge-Blum)*
    - topic: A Data Gathering Protocol for Wireless Sensor Networks
    - November 2005 – February 2006

23. **Mickaël Beaupoil** and **Valerian Meurant**
    - MEng student researchers, at INSA Lyon
    - topic: Evaluating the Energy Consumption and Real-time Characteristics of a Wireless Sensor Network
    - November 2005 – February 2006

0.4 Responsibilities

Standardization

1. Co-chair, IETF 6TiSCH Working Group.
2. Chair of the IETF 6lo Fragmentation Design Team.
3. Member of the IETF IoT Directorate.
4. Author of multiple IETF I-Ds and RFCs, see publications list below.

Volunteering

1. Member of the **Inria-Paris "Commission de Développement Technologique"**, since 2018, where we ensure Inria project teams get sufficient engineering resources to change the world.
2. Member of the **Inria-Paris "Comite de Centre"**, since 2016, where we work on making sure Inria-Paris will always remain one of the greatest places to work at!
3. **Senior member of the IEEE** since 2015.
4. **Member of the IEEE** since 2006, with membership to *IEEE Communications Society* (since 2006), *IEEE Internet of Things Community* (since 2015), *IEEE Industrial Electronics Society* (2014-2015), *IEEE Young Professionals* (since 2014), *IEEE Women in Engineering* (2007-2009).
5. Member of the **IEEE Region 8 Membership Activities Committee** as Electronic Communications Coordinator between January 2007 and December 2008.
6. Member of the **IEEE Region 8 Student Activities Committee** as Awards and Contests Coordinator between October 2006 and December 2008 .
7. Member of the **IEEE Region 8 Awards and Recognition Committee** as Student Activities Committee Representative between October 2006 and December 2008 .
8. Member of the **IEEE Wireless Communications Technical Committee,** 2007.
9. **Chair of the IEEE Student Branch Grand Lyon** between September 2006 and January 2007 .
10. Member of **ACM EuroSys**, 2006.

Organization

1. **TPC co-chair**, *6th International Workshop on Computer and Networking Experimental Research using Testbeds (CNERT)*, held in conjunction with *INFOCOM*, Paris, France, 29 April-2 May, 2019.

2. **Chair**, ETSI/F-Interop 6TiSCH interop event #5, Paris, France, 26-27 June 2018.

3. **Chair**, ETSI/F-Interop 6TiSCH interop event #4, IETF 99, Prague, Czech Republic, 16-21 July 2017.

4. **General co-chair**, *IOT2SUSTAIN invited workshop*, UCL campus, London, 6-7 July 2017.

5. **General co-chair** with Fabrice Theoleyre and Antoine Gallais of a special session on "Industrial Internet of Things: Constraints, Guarantees, and Resiliency" at the 23rd *IEEE International Conference on Telecommunications (ICT)*, Thessaloniki, Greece, 16-18 May 2016.

6. **Technical Program Committee Chair and Local Chair**, *EAI Conference on Interoperability in IoT (InterIoT)*, Paris, France, October 2016.

7. **Demo Chair**, *IEEE International Conference on Sensing, Communication and Networking (SECON)*, London, UK, 27-30 June 2016.

8. **Chair**, ETSI 6TiSCH interop event #3, IETF 96, Berlin, Germany, 17-22 July 2016

9. **Chair**, ETSI 6TiSCH interop event #2, Paris, France, 2-4 February 2016.

10. **Technical Program Committee Chair**, *EAI Conference on Interoperability in IoT (InterIoT)*, part of the IOT360 Summit, Rome, Italy, 28-29 October 2015 [**13 companies participating**].

11. **Chair**, *OpenWSN/6TiSCH Hackathon*, Czech Republic, 19 July 2015.

12. **Chair**, ETSI 6TiSCH interop event #1, IETF 93, Prague, Czech Republic, 17-18 July 2015 [**15 companies participating**].

13. **Program co-chair** of the *1st International Workshop on IoT challenges in Mobile and Industrial Systems (IoT-Sys)*, in conjunction with MobiSys, Florence, Italy, 18 May 2015.

14. **Chair**, 6TiSCH plugfest #2, IETF 90, Toronto, Canada, 20-25 July 2014

15. **Chair**, 6TiSCH plugfest #1, IETF 89, London, UK, 2-7 March 2014.
16. **Member of the organizing team** of the *IPSO Interoperation* event "IEEE802.15.4e TSCH and CoAP", Santa Clara, CA, USA, 11-12 October 2011.
17. **Co-chair** of the *BSAC Hands-On Workshop*: Networking Wireless Inertial Sensors, co-located with the Berkeley Sensors and Actuator Center's IAB, UC Berkeley campus, Berkeley, CA, USA, 15-17 September 2010.
18. **Member of the organizing team** of the *Robot Fair, UC Berkeley* campus, Berkeley, CA, USA, 11 July 2009.
19. **Publicity Chair** of the *International Workshop on Simulators for Wireless Networks (SWiN)*, part of IEEE WiMob 2008.
20. **Web Chair** for the *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Cannes, France, 14-18 September 2008.
21. General co-chair for *First International Conference on Simulation Tools and Techniques for Communications, Networks and Systems (SIMUTools)*, Marseille, France, 3-7 March 2008.
22. **Web Chair** for *Second International Conference on Body Area Networks (BodyNets)*, Florence, Italy, 11-13 June 2007.
23. **Organization Committee member** of the *IRAMUS Workshop*, Val Thorens, France, 25-26 January, 2007.
24. **Staff Chair** of 32nd Annual Conference of the *IEEE Industrial Electronics Society (IECON)*, Paris, France, 7-10 November 2006.
25. **Organization Committee member** of the *IEEE Region 8 Student Branch and GOLD Congress (SBC)*, Paris, France, August 31 – September 3, 2006.

Thesis Reviewer

1. Member thesis review committee (as reviewer) of **Jetmir Haxhibeqiri**. Doctoral work on "*Flexible and Scalable Wireless Communication Solutions for Warehouse Applications*" done at imec – IDLab Ghent – **Ghent University, Belgium**, under the supervision of Jeroen Hoebeke. Viva on 6 December 2018.

2. Member thesis review committee (as examiner) of **Remy Leone**. Doctoral work on "*Intelligent Gateway for Low-Power Wireless Networks*" ("Passerelle intelligente pour réseaux de capteurs sans fil contraints" in French) done at **Telecom ParisTech, France**, under the supervision of Jean Louis Rougier and Vania Conan. Viva on 24 June 2016.

3. Member thesis review committee (as examiner) of **Kevin Roussel**. Doctoral work on "*Evaluation et amelioration des plates-formes logicielles pour réseaux de capteurs sans-fil, pour optimiser la qualite de service et l'energie*" done at **Inria Nancy, France**, under the supervision of Ye-Qiong Song and Olivier Zendra. Viva on 3 June 2016.

4. Member thesis review committee (as examiner) of **Antonio O. Gonga**. Doctoral work on "*Mobility and Multi-channel Communications in Low-power Wireless Networks*" done at **KTH Electrical Engineering, Sweden**, under the supervision of Prof. Mikael Johansson. Viva 14 January 2016.

5. Member thesis review committee (as examiner) of **Roudy Dagher**. Doctoral work on "*Sur la radionavigation dans les villes intelligentes du futur – Le cas des réseaux de capteurs sans fils*" done at **Inria-Lille, France**, under the supervision of Nathalie Mitton. Viva on 6 October 2015.

6. Member thesis review committee (as examiner) of **Georgios Z. Papadopoulos**. Doctoral work on "*Improving Medium Access in Dynamic Wireless Sensor Networks*" done at **University of Strasbourg, France**, under the supervision of Antoine Gallais and Thomas Noel. Viva on 28 September 2015.

Project Reviewer/Advisory Board Member

1. Project Proposal reviewer for **Flanders Research Fund (FWO)**, Belgium, 2015.

2. Member of the **Texas Instruments Expert Advisory Panel** since 2010.

3. Member of the Advisory Board of the **Calipso EU-FP7 Project**, 2012-2014.

4. **Book proposal reviewer (Wiley)**, 2011.

5. Project Proposal reviewer for the Fondo Nacional de Desarrollo Científico y Tecnológico (**Fondecyt**) de la Comisión Nacional de Investigación Científica y Tecnológica, **Chile**, 2010.

6. Project Proposal reviewer for the French Agence Nationale de la Recherche (**ANR**), 2009.

Editorial Duties

1. Editor, **EAI Transactions on Internet of Things**, 2015-2018.
2. Editor, **IEEE Internet of Things (IoT) Journal**, 2014-2016.
3. Guest Editor, **Computer Communications, Elsevier**, Special Issue on Networking and Communications for Smart Cities, 2014.
4. Guest Editor, **Transactions on Emerging Telecommunications Technologies, Wiley**, Special Issue on Machine-to-Machine: An Emerging Communication Paradigm, 2013.
5. Member of the **Editorial Board of IET Journal** on Wireless Sensor Systems since 2012.

Journal Reviewer

Regular reviewer for 35 different journals, including **IEEE Transactions on Industrial Informatics**, **IEEE/ACM Transactions on Networking**, and **IEEE Transactions on Parallel and Distributed Systems**. See `https://twatteyne.wordpress.com/resume/#journal` for a full list.

Technical Program Committee Member

Members of 46 Technical Program Committees as Member, including for flagship conferences IEEE ICC, IEEE PIMRC, IEEE VTC, IEEE SECON, and ACM EWSN. See `https://twatteyne.wordpress.com/resume/#tpc` for a full list.

Conference Reviewer

Numerous, see `https://twatteyne.wordpress.com/resume/#conference` for a full list.

0.5 Management

Research Teams

1. **Inria-EVA subteam**. I am managing / have managed the following members of my sub-team within Inria-EVA:

   (a) **(current)** Jonathan Munoz, PhD Student, Jan 2016 – March 2019, co-advised by Paul Muhlethaler (I supervise him at 95%)

(b) **(current)** Mina Rady, PhD Student, Jan 2019 – Dec 2021, co-advised by Paul Muhlethaler, Dominique Barthel, Quentin Lampin (I supervise him at 30%)

(c) **(current)** Tengfei Chang, postdoc, 2016 – 2020, I'm his primary manager (100%)

(d) **(current)** Keoma Brun-Laguna, postdoc, 2019, I'm his primary manager (100%)

(e) **(current)** Trifun Savic, Research Engineer, Feb 2019 – Oct 2020, I'm his primary manager (100%)

(f) **(current)** Yasuyuki Tanaka, Research Engineer, Jan 2018 – Dec 2019, co-advised by Pascale Minet (I supervise him at 40%)

(g) Keoma Brun-Laguna, PhD Student, Jan 2016 – Dec 2018, co-advised by Pascale Minet (I supervise him at 90%)

(h) Ziran Zhang, postdoc, Jan 2017 – Apr 2018, I was his primary manager (100%)

(i) Remy Leone, postdoc, 2017 – 2018, I was his primary manager (100%)

(j) Malisa Vucinic, postdoc, Oct 2016 – Sep 2017, I was his primary manager (100%)

(k) Felipe Moran, intern, Sep 2017 – Aug 2018, I was his primary manager (100%)

(l) Fabian Rincon Vija, intern, May – Aug 2018, I was his primary manager (100%)

(m) Marcelo Augusto Ferreira, intern, May – Aug 2018, I was his primary manager (100%)

2. **REALMS Associate team**. This is *not* a fully-fledged Inria team, but rather a collaboration between my team and Profs. Glaser's and Pister's teams in UC Berkeley and Prof. Kerkez at U. Michigan. The collaboration has run since 2015, and has resulted in 8 trips from France to the US, and 11 from the US to France. This collaboration has resulted in the publication of 4 journal articles and 2 conference papers. While I don't have an official affiliation with UC Berkeley, I have been mentoring the following PhD students specifically, in particular when preparing papers: Carlos Oroza, Sami Malek, Ziran Zhang. I hired Ziran Zhang on a 16 month postdoc position right after he graduated from the UC Berkeley team.

3. **DIVERSITY Associate team**. This is our second associate team, with Prof. Bhaskar Krishnamachari's team at the University of Southern California, which ran in 2016-2018. This associate team has resulted in 2 trips from France to the US, and 2 trips from the US to

France. While I don't have an official affiliation at USC, I have been mentoring PhD student Pedro H. Gomes. This collaboration has resulted in the publication of 4 journal articles, and 1 conference paper.

Research Projects

1. **H2020 F-Interop**. Nov 2015 – Oct 2018. I was work package leader, and co-lead of the Inria contributions, together with Prof. Cesar Viho from Inria Rennes.

2. **H2020 ARMOUR**. Feb 2016 – Jan 2018. I was work package leader. This project allowed us to work on secure joining in the 6TiSCH context, paying for Malisa Vucinic's 1-year postdoctoral stay in the team.

3. **H2020 SPARTA**. Feb 2019 – Jan 2022. This project just started, and aims at developing formal proofs on the OpenWSN protocol stack implementation.

4. **FUI GeoBot** 1 Sep 2018 – 30 Sep 2019. I am work package leader. This project is ongoing, and aims at creating a solution to locate and map underground gas pipes. Inria-EVA's role is to design the wireless localization solution.

5. **Stic-AmSud SaveThePeaches**. 2016 – 2017. I was co-leading the proposal writing, the lead of the Inria contributions.

6. **Stic-AmSud WirelessWine**. 2019 – 2020. This project just started, and aims at developing a frost prediction system for vineyards based on new long-range technology we have developed in the team.

7. **Inria-Silicon Valley Grant**. Jan 2017 – Apr 2018. I was lead of the project, and supervised Ziran Zhang, the postdoctoral researcher I hired on the project. This project is part of the SmartMarina research project and has lead to the creation of the Falco spin-off.

8. **France-Berkeley-Fund SHRIMP**. 2018. This project is part of the SmartMarina research project and has lead to the creation of the Falco spin-off.

9. **ADT OpenWSN**. 2016 – 2017. I was lead. This project has been the foundation of the OpenWSN development.

10. **ADT 6TiSCH**. 2018 – 2019. I am lead. This project aims at benchmarking the 6TiSCH protocol stack through the OpenWSN implementation running on the OpenTestbed.

11. **ATT SmartMarina**. Jan – Dec 2019. I am lead. The goal of this project is to develop the foundation technology for the Falco spin-off.

12. **EDF industry grant**. Summer 2018. I was lead. The goal of this project was to build a demonstrator of an indoor wireless localization solution.

13. **Orange Labs CIFRE**. 2019 – 2021. I am lead. This project funds Mina Rady, and aims at developing a hybrid low-power wireless solution which combined IEEE802.15.4g and LoRa.

14. **Gridbee CIFRE**. 2016 – 2018. I was lead. The startup closed after 2 years of the PhD student, Inria paid for his last year of salary. This project funded Jonathan Munoz, and aimed at developing km-scale deterministic networking technology.

Research Programs

1. **IPL RIOT-FP**. 2019 – 2022. This is a large Inria Project Lab which brings together several teams to work on security and dependability aspects of embedded networking. Inria-EVA's involvement is important, and aims at integrating the OpenWSN protocol stack into the RIOT operating system. The IPL RIOT-FP is well aligned with H2020 SPARTA. I'm offloading the leadership of this project to Malisa Vucinic who joined the Inria-EVA team in 2018 on an SRP contract.

0.6 Collaborations

The following sections are presented in semi-chronological order.

UC Berkeley, Pister Lab

After finishing my PhD, I did a postdoctoral stay in Prof. Pister's lab at UC Berkeley. That stay had an big impact on the way I work, as it shifted my focus very clearly towards "making things work" and building solutions to real-world problem. From a technological point of view, it's there that I was introduced to TSCH technology, which is now a significant part of my research.

I haven't stopped working with this lab since that time, through the following collaboration vehicles:

- Prof. Pister is the founder of the Dust Networks startup (now a group within Analog Devices), where I have been working.
- The REALMS associate team, which has been running since 2015, and which has allowed us never to stop working together.
- Our teams have planned to work together even more closely, as our research in the next 4-5 years is tightly intertwined.

Dust Networks, Analog Devices

I joined Dust Networks in 2011, and worked there full time for 4 years. I have been consulting with the Dust Networks group (now part of Analog Devices) while at Inria, on my 6TiSCH standardization activities.

UOC/OpenMote

Prof. Xavi Vilajosana was a visiting professor at UC Berkeley in 2012-2013, we were working very closely on the OpenWSN project. He is now a professor at the Open University of Catalonia (UOC), and founded the OpenMote startup to commercialize the OpenMote platform we had designed in the OpenWSN project. We have been working together very tightly. Prof. Xavi Vilajosana now co-leads the OpenWSN project, and is one of the core contributors to the 6TiSCH standardization activities. Members of our teams visit one another at least 3 times a year. While there is no funding involved in this collaboration, Inria-Paris and OpenMote signed a memorandum of understanding for the 2017-2020 period.

UC Berkeley, Glaser Lab

The REALMS associate team, which has been running since 2015, has allowed my team to collaborate with Prof. Glaser's lab at UC Berkeley. Specifically, this lab deploys sensors to monitor the snowpack in California, our team helps with the network aspects. This collaboration has resulted in numerous visits and joint publications. The goal for 2019 is to experiment with the long-range technology which we have developed during Jonathan Munoz' PhD.

University of Southern California

The DIVERSITY associate team, which ran in 2016-2018, allowed my team to collaboration closely with Prof. Bhaskar Krishnamachari's.

0.7 Teaching

Over the past 4 year, I have been developing a set of courses called "Dust Academy", which I detail in Section 6.3. Most courses I have taught in the past 4 years have been based on it.

- 2019
  - 1-day hands-on course on IIoT, and support of subsequent projects, MsC level, **University College London**, 6 February 2019.
- 2018

- Intensive 1-week course on IoT, with associated hands-on labs. **ENSTA ParisTech**. Graduate level. Together with Keoma Brun-Laguna, 1-5 October 2018.
- 1/2-day crash course on the Industrial IoT, **Telecom ParisTech**. Graduate level. 28 September 2018.
- "From Sensors To Sensor Networks", 2h class as part of the course given by Prof. Steven Glaser, **UC Berkeley**, 30 August 2018.
- 6-week course on IoT, with associated hands-on labs. Undergraduate level. **ENSTA ParisTech**. Together with Keoma Brun-Laguna and Dominique Barthel. Spring 2018.
- 1-day hands-on course on IIoT, and support of subsequent projects, MsC level, **University College London**, February 2018.

- 2017
  - Intensive 1-week course on IoT, with associated hands-on labs. **ENSTA ParisTech**. Graduate level. Together with Ziran Zhang, 9-12 October 2017.
  - 1/2-day crash course on the Industrial IoT, **Telecom ParisTech**. Graduate level. 28 September 2017.
  - 6-week course on IoT, with associated hands-on labs. **ENSTA ParisTech**. Undergraduate level. Together with Keoma Brun-Laguna and Dominique Barthel. Spring 2017.
- 2016
  - Intensive 1-week course on IoT, with associated hands-on labs. **ENSTA ParisTech**. Graduate level. Together with Keoma Brun-Laguna and Dominique Barthel, 12-15 December 2016.
  - 1/2-day crash course on the Industrial IoT, **Telecom ParisTech**. Graduate level. 5 October 2016.
  - 2h course of Industrial IoT at USC. Undergraduate level. April 2016.
- 2015
  - Intensive 1-week course on IoT, with associated hands-on labs. **ENSTA ParisTech**. Graduate level. Together with Quentin Lampin and Dominique Barthel, 12-18 November 2015.
  - [**MOOC**] [**over 20,000 registered**] Internet of Things (IoT) together Prof. Mischa Dohler from with King's College London, FutureLearn platform, first course on 23 November 2015. I'm also a Mentor on IoT on the FutureLearn platform since 2015.

- 1/2-day crash course on the Industrial IoT, **Telecom ParisTech**. Graduate level. 30 September 2015.
- 1h class on the Silicon Valley at **KULAK**, Kortrijk, Belgium. Undergraduate level. 17 March 2015.
- Intensive 1-week course on IoT, with associated hands-on labs. **ENSTA ParisTech**. Graduate level. Together with Quentin Lampin and Dominique Barthel, 19-23 January 2015.

• Earlier

- I taught the EE290Q: "Introduction to Wireless Sensor Networks" graduate-level course twice together with Prof. Kris Pister at **UC Berkeley**, during the Spring 2009 and Spring 2010 semesters.
- I taught the EE290Q: "Introduction to Wireless Sensor Networks 290Q" class together with Prof. Kris Pister, in the EECS Department at **UC Berkeley**, in the Spring 2010 semester. I taught half the classes, including:
  * Protocol stack, headers, encapsulation
  * Preamble sampling MAC protocols
  * SPI, IEEE802.15.4 frame format, IEEE802.15.4e
  * Flooding, geographic routing
  * 6LoWPAN, UDP, TCP
- I prepared and taught the hands-on lab of **UC Berkeley** EE290Q: "Introduction to Wireless Sensor Networks" class in the Spring 2009 and Spring 2010 semesters. The labs were done on the eZ430-RF2500, with support from Texas Instruments, and were the foundation of the (now very popular) eZWSN tutorials which you can find on Rice University's cnx.org [over 17,850 views], or on Amazon.com. The sessions included:
  * Lab 0: Installing the Environment
  * Lab 1: I/O, timers, interrupts on the eZ430-RF2500
  * Lab 2: energy consumption, wireless chat
  * Lab 3: spectrum analyzer, RSSI vs. distance
  * Lab 4: CRC, PDR vs. distance, preamble sampling
  * Lab 5: System Design
- I gave the class on "Routing in Wireless Sensor Networks: from Theoretical Concepts to Practical Solutions" in the Spring 2009 session of the EE290Q: "Introduction to Wireless Sensor Networks 290Q" in the EECS Departement at **UC Berkeley**.
- I was a teaching assistant (2005-2008), at **INSA Lyon**, Telecommunications Department, 3rd and 4th year engineering students. Hands-on labs, classes and exams. 118h total. Classes included:

* LAN/MAN/WAN (4th year students)
* Networking (3rd year students)
* Algorithms (3rd year students)
* Operating Systems (3rd year students)
* Network Modeling and Performance Evaluation (4th year students)

Invited Presentations *(selected)*

For a full list, see `https://twatteyne.wordpress.com/publications/#talks`.

1. *The Internet of (Important) Things.* French Tech Central, **Station F, Paris**, France. 24 October 2018.

2. *IoT research, standardization and interop using testbeds*, **Fed4FIRE Engineering Conference, Brugge, Belgium**, 8-9 October 2018.

3. *From Research, to Product, to Standardization: A Journey into TSCH.* **TU Graz, Graz, Austria**, 19 July 2018.

4. *Reality Check on IoT Solutions producing data for people to analyze.* Boston Consultancy Group seminar series, **Station F, Paris**, France. 7 July 2018.

5. *Industrial IoT, A Reality Check: Standards, Products and Research Challenges.* **IIoT Workshop, Strasbourg,** France, 3 July 2018.

6. *IPv6 over the TSCH mode of IEEE 802.15.4e: overview of standardization, tooling, open-source initiative and commercial products*, Workshop on Design, Deployment and Testing of Internet of Things Technologies (DDT-IoT), **IEEE BalkanCom, Podgorica, Montenegro**, 8 June 2018.

7. *Industrial IoT, A Reality Check: Standards, Products and Research Challenges*, **IoT Week, Bilbao, Spain**, 4-8 June 2018.

8. *Low Power Wireless Solutions for Industry 4.0: Products, Standardization, Research and Example Deployments.* Industry 4.0 Predictive Analytics and Forecasting: Research and Applications. **Siemens Corporate Technology, Munich, Germany**, 14-15 September 2017.

9. *From Smart Dust to 6TiSCH: Academic and Commercial Background on TSCH Technology*, Sensor Platform for HEalthcare in a Residential Environment (SPHERE) seminar, **University of Bristol, Bristol, UK**, 6 October 2016.

10. *A Not So Politically Correct Reality Check about the IoT.* **ACM MobiHoc, Paderborn, Germany**, 6 July 2016.

11. *HeadsUp! Long-Term Real-Time Patient Position Monitoring.* International Conference on Digital Sciences and Technologies for Health, **Futur en Seine Festival, Paris**, France, 10 June 2016.

12. *Overview (Industrial) IoT Standardization Efforts at IETF.* **ITU Meeting, Geneva, Switzerland**, 10 May 2016.

13. *Having fun with Industrial IoT*, **University of Southern California, Los Angeles**, CA, USA, 1 April 2016.

14. *Not-so-Politically Correct Food for Thought on NGIoT*, **US-Europe Invited Workshop on Next-Generation IoT (NGIOT), Los Angeles**, CA, USA, 31 March 2016.

15. *The Rise of the Industrial IoT.* **International Conference on Ad Hoc Networks (AdHocNets), San Remo, Italy**, 31 August-2 September 2015.

16. *From Smart Dust to 6TiSCH: building the Industrial Internet of Things.* 4th International Symposium on Sensor Science **(I3S), Basel, Switzerland**, 13-15 July 2015.

17. *Determinism in the IoT: the example of 6TiSCH and OpenWSN.* **IRTF T2TRG meeting, Dallas, TX**, USA, 22 March 2015.

18. *The Industrial IoT: Challenges, Solutions and Success Stories.* California France Forum on Energy Efficiency Technologies **(CaFFEET), San Francisco**, CA, USA, 19 November 2014.

19. *OpenWSN: Technical Overview, Status and Road Ahead!* **Swarm Lab Seminar Series, UC Berkeley**, 6 November 2014, Berkeley, CA, USA.

20. *The Internet of (Important) Things.* **DREAM Seminar Series, UC Berkeley**, 8 April 2014, Berkeley, CA, USA.

21. *Reliable Low-Power Mesh Networking with SmartMesh IP.* **IDTechEx Internet of Things and WSN USA, Santa Clara**, CA, USA, 19 November 2013.

22. *Designing and Implementing the Internet of (Important) Things.* **University of Luxembourg**, Interdisciplinary Centre for Security, Reliability and Trust (SnT). 15 July 2013.

23. *IETF 6TSCH: a New Standardization Effort to Combine IPv6 Connectivity with Industrial Performance*. Webinar hosted by the **MEMS Industry Group**. 10 June 2013.

24. *Standards-based Reliable Wireless Sensor Networking*. Conference on Sensors, Technology, Design, and Applications **(SensorsCon), Santa Clara**, CA, USA, 21 March 2012.

Part II

Scientific Report

Chapter 1

Introduction

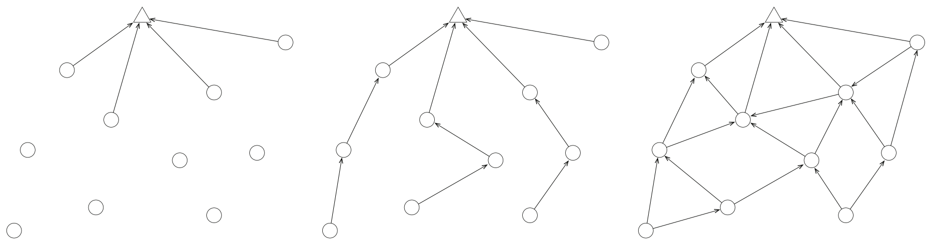
This manuscript is an opportunity for me to discuss the research I have been doing since my PhD. It does not contain any of the research I have done during my PhD. My goal is to take the reader through a journey, and focus on four different themes which I have been exploring. For each, my goal is to describe why I think they are interesting, how I have approached them, and what results I have obtained. This manuscript makes no attempt at replicating the different publications I have made. It is in that sense not a self-sufficient technical document, but rather a description of how my contributions string together. I attempt, throughout the manuscript, to give my personal view on my research domain, and the road ahead.

To avoid long tedious lists, I'm not attempting in this manuscript to give a full survey of the related work in the field. I do cite some key related work throughout the manuscript, and cite my own publications in an attempt to describe how they fit together. Each of my publications contains a rigorously analysis of the state of the art related to that particular paper, which I invite the interested reader to go through.

This chapter introduces the fascinating technology of low-power wireless mesh networks, and stresses the importance of the link-layer in the performance of these networks. The next chapter will focus on how my research fits into that research domain, and how I decided to structure this manuscript.

1.1 Low-Power Wireless Mesh Networking

There are three elements which make low-power wireless mesh networking, and the Internet of Things [1, 2], such a fascinating technology. First, it is a complicated technology; it is particularly complicated to make a network that is both reliable and low-power. Second, it is a generic networking technology that applies to a plethora of applications, for which there is a real market demand. Finally, from a research topic point of view, it allows one to go from concept to real-world deployment with reasonable means,



(a) A star topology. (b) A tree topology. (c) A mesh topology.

Figure 1.1: Different ways of logically organizing a network of devices around a gateway.

and is perfectly scaled to be addressed by a 3-year PhD program, of a 1-year post-doctoral stay. It is a technology that has captured the imagination of scholars, students and the public alike.

Low-power wireless mesh networks are used in applications where a large number of sensing or actuation points are needed in a particular area of interest. One example is to verify the state of every valve in an oil refinery or another industrial application [3, 4, 5, 6, 7, 8, 9, 10]. Another is to do micro-climatic monitoring in smart agriculture [11, 12, 13, 14]. A third is to monitor the occupancy of every parking space in a city [15, 16, 17, 18]. These are all real examples which use low-power wireless mesh networks.

Low-power wireless mesh networks allow each of these points to be equipped with a small matchbox-sized electronic box which does the sensing and actuation and requires no wires for an operator to receive the sensors measurements or send actuator commands. Each of these nodes – often called "motes", in reference to the Smart Dust research project which contributed in defining the field – contains sensing/actuation, computation and communication capabilities. These motes always contain a micro-controller and a radio chip (sometimes combined into one system-of-a-chip), and are typically powered by a battery.

The radio inside a node allows for the mote to communicate with other motes. One mote plays the role of the gateway, which typically connects the low-power wireless network to some computer network, or directly to the Internet. These gateways are typically mains powered, as they run much more powerful software than the motes. The fact that the gateway requires both power and Internet connectivity, makes it much harder and more costly to install, so users typically want to reduce the ratio of gateways versus motes to a minimum.

With these constraints in place, the role of the networking software running on the motes (which is the focus of my research) is to efficiently connect the mote to the gateway. There are three ways of doing so, which are depicted in Fig. 1.1.

The simplest way is to form a "star": each mote directly communicates with the gateway. The main advantage of this approach is its simplicity (and the fact that it is easier to explain to end users), and allows the motes to turn on their radio strictly when they have something to transmit, which makes them very energy efficient (see below). The main disadvantage is that, in case the motes are out of range of the gateway, they cannot participate in the communication.

To get around that, a first technique is to let motes relay data from one another, and form a multi-hop "tree" topology that is rooted in the gateway. This way, when a node that it out of range of the gateway needs to report a sensor measurement, it hands that measurement to another node that is closer than itself to the gateway, resulting in multi-hop communication. This solves the connectivity issue of a star, but requires enough motes to be installed so that there is a multi-hop path between each mote and the gateway. One problem with this type of topology is that, if one of the relaying motes is switched off, all of its descendants in the network are disconnected. And while the network can self-heal from such a situation, during the repair process data is likely going to be lost.

The most advanced topology is the "mesh", which is a tree to which one has added redundant paths. That is, each mote has at least two neighbors it can send data to. The main advantage is that a mote can be switched off at any time, without impacting the flow of data.

Mesh networks are the most advanced of these technologies, but also the most challenging to design, which makes them a very interesting research topic. There is an inherent trade-off between 4 elements in these networks: the amount of data each mote can generate, the end-to-end latency of the communication, the end-to-end reliability, and the energy consumption. Specifically, the three first trade-off with the last. That is, to be able to transport more data, with a lower latency and a higher reliability, the network will consume more energy and have a shorter battery lifetime.

Making these networks be reliable is one of the main challenges. The reason is that wireless is unreliable in nature. Sometimes, even when two devices are very close together in a space that looks clutter-free, they are not able to communicate. Chapter 3 is entirely dedicated to this aspect.

Since my research is very hands-on, I believe it is important to introduce the type of hardware a low-power wireless mote is composed of [19]. Fig. 1.2 shows the OpenMote B, a popular mote that represents the state of the art at the time of writing, and which is popular in the low-power wireless research community [20, 21, 22]. As on every electronic component, there a number of passives, signal conditioning, USB connectivity and power management circuitry that takes up a lot of the real estate on the board. The real core of the mote is its micro-controller (CC2538) and radio chip (AT86RF215).

The micro-controller executes the firmware one puts on it, and which typically contains the networking software (the "protocol stack") and the software that interfaces to sensors and actuators. Despite the fact that

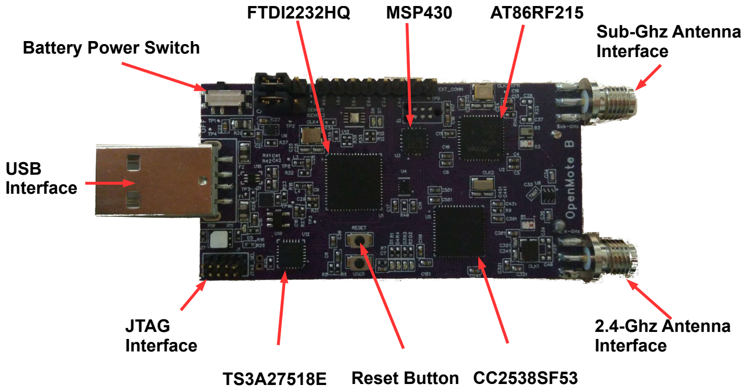


Figure 1.2: The OpenMote B platform.

micro-controllers evolve quickly (from the decade-old 16-bit MSP430 to today's 32-bit ARM Cortex series) the programming model stays the same: the software executes short bursts of code each time a event happen (a timer expires, a sensor flags a new sensor reading available, etc). In a typical implementation, the micro-controller wakes up a couple of times a second, each time for less than one milli-second. And since the micro-controller typically consumes less then 5 mA, the overall charge drawn by the micro-controller is small.

The radio is the second key element in the mote, as it gives the mote its communication capability. The radio is slaved to the micro-controller, so it is the networking software that decided when the radio is turn on and off. In low-power wireless networking, the networking software has typically very fine control over the state of the radio. When on, the radio can either be in transmit or receive mode. In the latter case, it is either listening for a frame, or actively receiving a frame sent by a nearby mote. Regardless of whether the radio is in receive or transmit mode, it draws about the same amount of electrical current, typically in the 5-20 mA range for IEEE802.15.4-compliant radios communicating at 2.4 GHz. With that configuration, it takes about 4 ms for the radio to fully transmit or receive a 127 B frame. Given these numbers, it is clear that, to make a mote last for a long time on a battery, we need to focus our attention towards optimizing radio utilization.

The networking software consists of a number of protocol, which are organized in layers. Three layers have received the most attention from

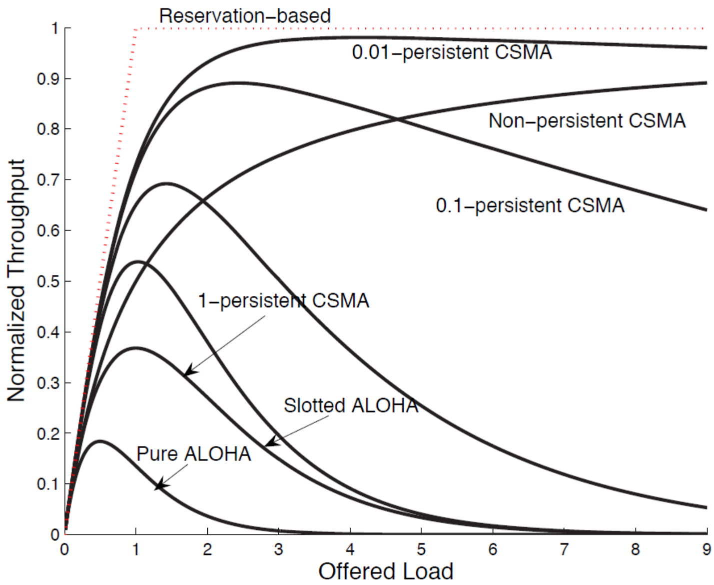


Figure 1.3: Qualitative throughput comparison between reservation (dotted line) and contention-based (solid lines) MAC protocols. *Taken from [26].*

the research community: application, network, and Medium Access Control (MAC). The most used application layer protocols in these types of networks are CoAP [23] and MQTT [24]. For a survey of routing-layer and MAC-layer protocols, the interested reader is referred to [25] and [26], respectively.

1.2 The Importance of the MAC Layer

I wanted to dedicate a section to the importance of the MAC layer, at least so it appears in the table of contents. The MAC layer is, in my experience, the layer with the most impact on the overall performance of the protocol stack. The techniques used at the MAC layer completely controls the amount of data the nodes can produce, the latency of the communication, the reliability of the network, and the power consumption of the mote. As per Section 1.1, these are all the key performance indicators of the network.

For some reason, certainly in the standardization activities I witness, the impact of the MAC layer is underestimated. Discussions tend to be more focused on topics such the integration of IPv6, or the way sensor data is represented. From my entrepreneurial point of view, what really matters to a customer is whether she can count on the low-power wireless network to deliver all of her data fast, and whether she will have to change batteries often. These are all MAC-layer issues.

The MAC layer decides when the radio is turned on and off, and on which frequency. While this manuscript isn't the place to survey MAC layer protocols, I want bring up Fig. 1.3 from [26]. It shows a comparison of the throughput of the three classes of canonical MAC approaches: Aloha, Carrier Sense Multiple Access (CSMA) and reservation-based. Given the clear performance advantage of reservation-based MAC protocols (the normalized throughput does not collapse as the offered load increases, and plateaus at 100%), after writing [26], I have dedicated a good portion of my research to studying Time Synchronized Channel Hopping (TSCH), a type of reservation-based MAC protocols (Chapter 3).

1.3 Summary

This chapter gives a quick introduction about low-power wireless networking. Space limitations prevent me from providing a complete overview of the technology. Rather, I introduce the key concepts which I develop in the remainder of this manuscript: use cases, overview of the hardware, topologies, and the importance of the MAC layer. Chapter 2 positions my research in this domain.

Chapter 2

Positioning

Before delving into the core of the manuscript, I want to describe how I see the positioning of my own research with regards to the community. The statements I make in this manuscript are sometimes controversial. As a researcher with some experience in the field, I have built some opinions about these systems, and am always looking for opportunities to be proven wrong and build better opinions. I'm hence writing this chapter on purpose in a direct discussion style, in order to spark these discussions.

2.1 My Personal Analysis of the State-of-the-Art

I make no attempt at providing a traditional state-of-the-art (for which I refer the interested reader to our Proceedings of the IEEE 2016 and 2019 publications [27, 28]), but rather focus on presenting my personal analysis.

TSCH is a bidirectional low-power wireless networking technique in which all nodes in a network are synchronized, and all communication is orchestrated by a schedule. This schedule indicates, for each of the timeslots (typically 10 ms long) whether to transmit, listen or sleep. When communicating, neighbor nodes "channel hop", i.e. they change frequency for each frame, according to a pre-agreed pseudo-random hopping pattern. The network organizes as a multi-hop mesh network, around one or more gateway devices. The schedule can either be managed in a central or distributed fashion. As discussed in Chapter 3, time synchronization allows the nodes to switch off their radio most of the time; channel hopping combats external interference and multipath fading, yielding wire-like reliability.

The TSCH concept is not new, it is used by Bluetooth and cellular communication. It was, however, introduced to low-power wireless by UC Berkeley Prof. Pister's team, and is now used in the WirelessHART, ISA100.11a and IEEE802.15.4-2015 standards. Commercial products, such as Analog Devices' SmartMesh product lines (which has been available since 2006), offer ¿99.999% end-to-end reliability, certified security, and over a decade of battery lifetime. Over 76,000 SmartMesh networks operate today, in 120 countries. TSCH has been an off-the-shelf technology for years.

There has been a surge in academic interest about TSCH in recent years (our standardization activities in the IETF 6TiSCH working group have been part of that). 6TiSCH/TSCH is now supported by all major open-source implementations (OpenWSN, Contiki, RIOT, TinyOS). Excellent research is being done by the groups leading those implementation efforts. One is Simon Duquennoy, who in 2018 announced Contiki-NG [29], a fork of the main stack focused entirely on 6TiSCH. In his IEEE SenseApp 2016 paper [30], Duquennoy shows ¡2μs synchronization accuracy for a 3-hop deep network, all motes sitting on a table. Our joint Sensys 2015 paper [31] shows over 99.99% end-to-end reliability. These results are much better than what is commonly presented in academic publications, and are creating a real stir in the academic community.

Yet, these results are still falling behind on commercial products. SmartMesh IP, for example, offers vastly better performance numbers: 99.999996% (seven nines) of reliability reported in actual industrial deployments [32], ¡4μs synchronization accuracy for a 5-hop network across the -40 C to +85 C temperature range, and a decade of battery lifetime. This absolutely does not invalidate the research stated above, but *it must force us to think about what we are doing as academics, and why.* In an academic setting, no matter how brilliant people are, there are simply not as many resources to implement and test as you have in a Silicon Valley company. A university lab cannot (and should not) afford to test an implementation for 4 months (the typical duration at Dust Networks) before a release. Rather, academic research ought to explore novel high-risk-high-gain paths, and, for the ones that work, collaborate in a symbiotic manner with the industry.

It is in that spirit that I am conducting my research. I have three guiding principles. First, by keeping track of what the industry is doing, I try not to "reinvent the wheel". If there is a proven off-the-shelf technology that works, I don't artificially recreate it for the sole satisfaction of having made it myself. Second, by interacting with as many stakeholders as possible, including outside of the low-power wireless research community, I try to understand what the real end-user needs are. The goal here is to work on problems that matter, and avoid addressing artificial problems because they are fun to solve (although that is hard). Third, I try to organize the research towards building a Minimal Viable Product (MVP), something tangible which can be shown and ideally used by end users. The goal here is to develop technology that is easily transferable through standardization, spin off activities, or partnerships with the industry. I know that these principles read naive and simplistic, and that it is impossible to abide by them in every occasion. But they are a general direction and goal I give myself.

I have had the privilege of working from both the academic research and entrepreneurial point of views. After a 2 year postdoctoral stay in Prof. Pister's team at UC Berkeley, I transitioned from his academic lab to his startup company, Dust Networks. I worked full time for Dust Networks[1] in 2011-2014, but kept close ties with the university, in particular through the OpenWSN project (see Section 3.3).

Dust Networks develops and commercializes low-power wireless mesh networking solution, under brand name "SmartMesh". The SmartMesh IP product line was commercialized in 2011. Today, SmartMesh IP is the best-in-class TSCH product, which offers ¿99.999% end-to-end reliability, ¡50μA average current draw for all devices[2], ¡15 μs synchronization error across the entire network. Over 76,000 SmartMesh networks operate today in over 120 countries, making it the market leader. SmartMesh IP received the prestigious "**ACE IoT Product of the Year**" award in December 2017. The following papers provide a technical description of SmartMesh IP: [33, 34, 35, 36]

Since having joined Inria in 2015, I have still been consulting for that team. These two sides of my work allow me to stay aware of what end users need and what the industry is building, which simplifies me following the principles outlined above.

2.2 How I'm Organizing this Manuscript

I organize the core of this manuscript in four chapters (Chapters 3-6), each covering a specific theme which I believe is key to this field. The chapters are organized so they provide a logical progression, somewhat chronological, which reflects my journey through this research field.

Chapter 3 starts by addressing the concept of "**dependability**", which is central to any critical application, including industrial applications (to which "important things" in the title of this manuscript refers). I first define the term dependability as related to a technology one can count on, and describe the challenges to make a low-power wireless networks reliable. I then introduce Time Synchronized Channel Hopping, the MAC-layer technique I have most closely studied, and OpenWSN, our open-source implementation of it, before listing some of the research we have been doing on TSCH.

Chapter 4 focuses on the **standardization** process, and how I have been involved in it. I start by describing the process itself, hopefully debunking the myth that it is a sterile administrative task, then detail the work we have been doing in the IETF 6TiSCH standardization working group I have set

[1] Through a series of acquisitions, Dust Networks is now part of Analog Devices.

[2] Assuming a 100-node network, 5 hops deep, each node powered by pair of AA batteries (2200 mAh), each node sending 90 B of application-level data every minute, the nodes consume on average between 20.7 uA (15 years of battery lifetime) and 35.8 uA (9 years of lifetime), depending on their location in the network.

up and co-chair. The second half of the chapter is dedicated to presenting the research that has come out of my standardization work.

Chapter 5 looks are the **experimental evaluation** of the low-power wireless technology we have developed. Specifically, I give an overview of the testbeds the research community has been using, and how they participate in the general movement of "building things". The last third of the chapter provides a critical analysis of testbeds, and compares characteristics of their wireless connectivity to that of real-world deployments.

Chapter 6 makes the case for a system-level approach to low-power wireless networking. Now that the community has produced networking technology that works, I argue that, as a community, there is great benefit in building complete sensor-to-cloud solutions that answer real needs. I describe 5 real-world deployment projects, and the long-term dense connectivity dataset they we have been collecting from them. The second half of that chapter details the research we have been able to carry out thanks to these deployments.

Finally, Chapter 7 is not a conclusion. Rather, it provides a summary of the main lessons I have learnt so far, and details 3 avenues of high-risk-high-gain research I believe are key to pursue.

2.3 Summary

This chapter positions my research within the low-power wireless networking community. I start by giving my personal analysis of the state-of-the-art, highlighting the importance of a symbiotic relationship between academic research and the industry. In the second half of this chapter, I detail how the remainder of this manuscript is organized, chapter by chapter.

Chapter 3

Dependability in the IoT

The definition of dependability was given to me by Prof. Kay Römer from TU Graz during EWSN 2016. I think it captures the need extremely well, and I have adopted it since. When I think of a dependable system, I think of something I can "count on" [37]. That is, if I have a critical system I need to monitor, I know that I can use a particular technology for doing the job, that I can depend on it.

This concept of dependability is very close to what are known as "industrial requirements". I always think of an industrial plant such as a refinery, in which a low-power wireless system is used to assist the workers in monitoring and controlling the industrial process. First, the network needs to deliver all the measurements from the dozens of pressure sensors installed on a piece of tubing. Second, if the pressure it too high, the network needs to deliver the command that tells the valve to open to lower the pressure. Third, a hacker sitting in a van right outside the gates must not be able to connect to the low-power wireless network, understand the sensor reading, or send commands. Here, the "critical" aspect of the system is that, if the network fails in any of these three tasks, the consequences are serious, from factory downtime to electronic sabotage.

The reason I like the term dependable is that it encompasses the three aspects from the story above: end-to-end reliability, latency guarantees, security. And these are the three aspects I have always considered when designing and working with low-power wireless technology. Of course, the refinery example is very "industrial", and is there to get the points across. In reality, I have also been working with systems that can be considered less critical (e.g. monitoring a peach orchard), but I always argue that a technology is either secure, either reliable or not. Even applications perceived as "less critical" greatly benefit from dependable systems, i.e. we are not lowering the quality of a solution because the application is perceived as less critical. That is, if it works in a refinery, it will work in a peach orchard.

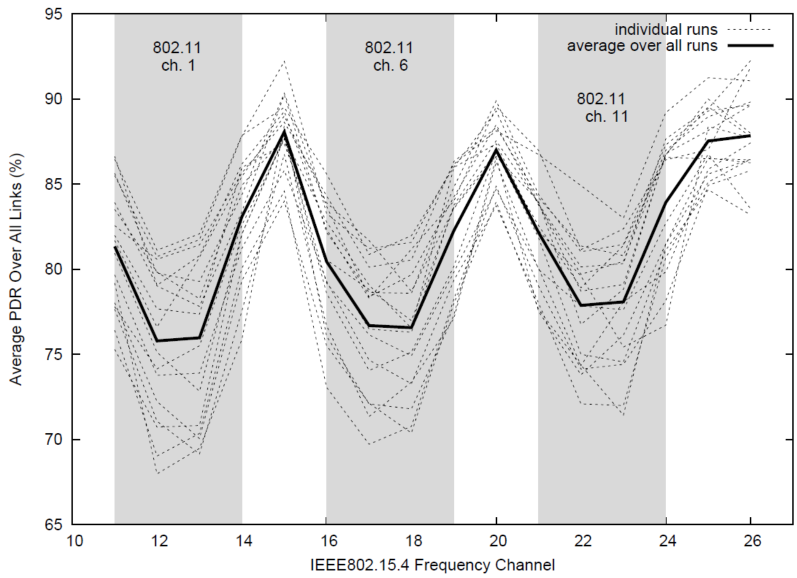


Figure 3.1: Nearby 2.4 GHz WiFi access points impact the performance of an IEEE802.15.4 network. *Taken from [38].*

3.1 The Challenge of Wireless

From a researcher point of view, what excites me about building dependable systems is to make something that works perfectly. In my mind, this means understanding exactly what causes the system to fail, and design a fix for that.

One of the first studies I did after finishing my PhD was understanding what the challenges of wireless are. Wireless is unreliable in nature, but what exactly is going on that causes a network not loose data? Together with the help of Prof. Culler at UC Berkeley and Dr. Lance Doherty at Dust Networks, I created the following figures. Fig. 3.1 shows how external interference is a major challenge. It shows the impact of 2.4 GHz WiFi on an IEEE802.15.4-based low-power wireless network; the quality of the communication is clearly worse in the grey bands which is where Wi-Fi is operating [39, 40, 41, 42, 43, 40]. We presented the paper containing Fig. 3.1 at PE-WASUN'09 [38], and I consider that paper (and figure) to be foundational for my research.

The second challenge is multi-path fading: the signal bounces off objects between the transmitter and the receiver, causing multiple echoes to reach the receiver. At particular positions of the receiver, these different echoes have offsets in time and signal strength such that they cancel out [45, 46]. This is very odd: even when the receiver is in theory more than close enough to the transmitter, they cannot communicate. Fig. 3.2 shows that happening in a real deployment in an industrial printing facility. If shows the quality of

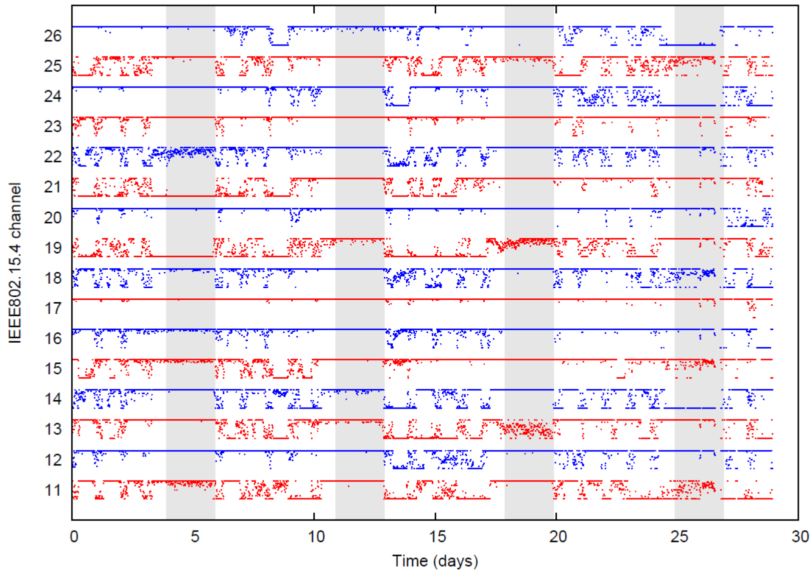


Figure 3.2: Multi-path fading causes the quality of a link to evolve over time differently on each frequency. *Taken from [44].*

a particular link evolving over time, for each of the 16 frequencies available in the 2.4 GHz range for an IEEE802.15.4-compliant radio. There is not a single frequency that is always good, and the subset of "good" frequencies is different from link to link. Fig. 3.2 was created using a dataset the Dust Networks people gathered during one of their early test campaigns, and made available to me for writing our WSNPerf'09 paper together with Branko Kerkez from UC Berkeley I was collaborating with [44].

Wireless never ceases to amaze me. There is something magical about two devices communicating without any visible connection between them. Because it is so satisfying to be able to explain some characteristics of this wireless communication, I've always enjoyed participating in these wireless measurement studies. The examples above are very early on. More recently, together with Cedric Adjih right after joining Inria, we did a similar measurement campaign on the FIT IoT-lab, and observed the same behavior [47]. We also witnessed these phenomena on TutorNet, the testbed Prof. Bhaskar Krishnamachari has deployed at the University of Southern California [48], and which we analyzed with Pedro Gomes (USC PhD student) as part of the DIVERSITY associate team between our labs.

3.2 Time Synchronized Channel Hopping

Figs. 3.1 and 3.2 clearly show that not all frequencies are equivalent, and that a single frequency isn't stable over time. It becomes clear that one

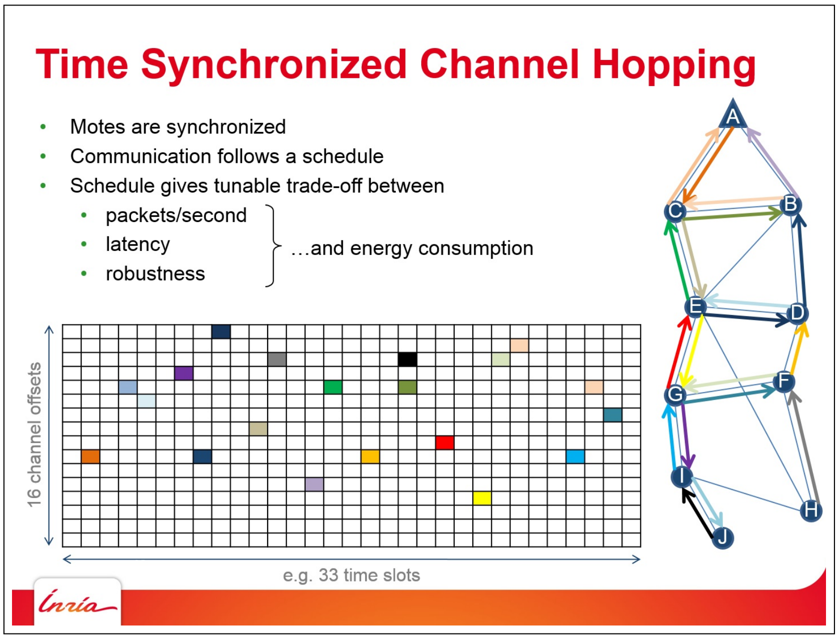


Figure 3.3: Time Synchronized Channel Hopping explained in a single slide. *Taken from the material presented during a course at University College London on 6 February 2019.*

cannot build a dependable low-power wireless network running on a single frequency. After these observations, I started working on a MAC technique called Time Synchronized Channel Hopping (TSCH). This is a well known technique for combating external interference and multi-path fading [49, 50], and is used in many narrow-band technologies, from Bluetooth to cellular networks. At the time, somewhat surprisingly, it hadn't been widely applied to low-power wireless systems. The team that was leading is development was Prof. Pister's team at UC Berkeley, and Dust Networks, the start-up company that had spun off that team. I hence joined that movement and have been spreading the TSCH message since.

Fig. 3.3 illustrates how TSCH works. In a TSCH network, all nodes are synchronized (typically to within 10-100 μs, depending on the implementation) and time is cut into timeslots. During one timeslot, two neighbor nodes can exchange a data frame and a link-layer acknowledgment. A data packet is typically about 4 ms long, an acknowledgment about 2 ms. Taking into account the time needed for the computation to take place, and the different guard times for taking into account de-synchronization, a timeslot duration of 10 ms it typical. A schedule orchestrates all communication, and tells each node what to do in each timeslot: transmit, listen or sleep. The key is that the y-axis in that communication schedule is a channel index, which translates to a different frequency each time the slotframe repeats, resulting in channel hopping. That is, each time two neighbor nodes exchange data, they do so at a different frequency. How this schedule is built is the key research challenge, as it trades off the number of packets per second nodes can generate, the latency and robustness of the network, against energy consumption.

TSCH fascinated me from the moment I learned about it. The base of the technology is simple and "makes sense", but there appear to be almost infinite trade-offs and optimizations that can be applied to it. I hence started a number of studies to answer some of the fundamental questions I was asking myself about this technology.

Together with UC Berkeley PhD students Ankur Mehta and Branko Kerkez [38, 44], I convinced myself that a single-channel solution could yield the level of dependability highlighted above. In our ICC'10 paper [51], we confirmed that channel hopping is very efficient at combating multi-path fading. The reason is simple: if node A fails to send a frame to node B at frequency f_1 (i.e. it doesn't receive a link-layer acknowledgment), it has a higher probability of succeeding if both nodes retry at a different frequency f_2. In [51], we introduce the concept of coherence bandwidth. The coherence bandwidth is the smallest frequency offset $\Delta f = |f_2 - f_1|$ which yields the highest probability of success of the retry. If the link is 5 m long or more, a Δf of as little as 5 MHz is sufficient [1]. This is very convenient as 5 MHz is also the frequency offset between adjacent channels in IEEE802.15.4. In practice, this means that, if a transmission fails on a particular frequency, just retry on any other frequency.

Much more recently, together with my Inria PhD student Jonathan Muñoz, we showed that the concept of channel hopping applied even to OFDM modulation [52]. This is entirely counter-intuitive (at least to me). OFDM with frequency repetition enabled essentially exploits frequency diversity at the physical layer by encoding the same data onto multiple sub-carriers at the same time. Channel hopping (which exploits frequency diversity at the MAC layer) therefore looks redundant. But an OFDM channel, as defined by the IEEE802.15.4g standard at 2.4 GHz, is only 1.094 MHz wide, so multi-path fading can affect all sub-carriers in the channel. We show, by analyzing a connectivity dataset of 141,587,000 data points collected over 21 days, that it makes sense to combine both OFDM and channel hopping.

3.3 OpenWSN

We conducted the experiments described above with software and hardware specifically crafted for these experiments. It became quickly clear that, to be able to thoroughly test new TSCH-related ideas, we needed the source

[1] This are measured results in our particular environment and may not hold in the general case

code of a TSCH implementation. Around 2010, a handful of companies were selling TSCH-based products. While these products worked beautifully well, we did not have their source code and hence couldn't implement our research ideas.

I hence created the OpenWSN implementation in 2010-2011, initially targeted at providing an open-source TSCH implementation to the research community. I have developed OpenWSN first by leading the OpenWSN team at UC Berkeley (4-5 people, mostly PhD students), with whom we had weekly meetings and "unplug" parties. I continued developping OnenWSN through the OpenWSN ADT project when arriving at Inria. OpenWSN is at the core of our research, and my entire team now contributes to it.

OpenWSN implements a TSCH-based protocol stack[2] and an application framework. It has been ported to 11 hardware platforms, from decade-old MSP430-based motes to state-of-the-art Cortex-M multi-radio boards. It comes with an emulator, so development/testing can be done on a computer [53]. The toolchains used are IAR EW430, IAR EWARM, MSPGCC, GCC and ARMGCC. The kernels used are uC/OS-II, FreeRTOS, RIOT and OpenOS [54].

OpenWSN now has over 60 direct contributors to its source code. It has been chosen as reference 6TiSCH implementation by ETSI, used as "Golden Image" for 6TiSCH plugtests. The project received funding and contributions from a variety of sources, mainly industrial (Texas Instruments, Atmel, STMicro, Analog Devices) but also public (Inria, European Projects H2020 F-Interop and H2020 ARMOUR). Several companies are building products based on OpenWSN, including most recently the HOBOnet product line[3] by OnSet.

OpenWSN has been the foundation of most of the experimental work we have been doing in my team. OpenWSN has also triggered the creation of OpenMote[4], its hardware spin-off, founded by Prof. Xavi Vilajosana, and which has sold thousands of their platforms. Prof. Xavi Vilajosana was a fullbright visiting professor at UC Berkeley in 2012-2013, with whom we have not stopped collaborating since. We have signed a Memorandum of Understanding between OpenMote and Inria-Paris. Vilajosana is now co-lead of the OpenWSN project and a core contributor to 6TiSCH, the standardization activities around it.

[2] This is now known as the "6TiSCH protocol stack" which we are standardizing at the IETF, see Chapter 4

[3] `https://www.onsetcomp.com/hobonet`

[4] `www.openmote.com`

3.4 An Academic Goldmine

Having OpenWSN has been a real enabler for me in conducting TSCH-related research. OpenWSN has allowed us to explore new ideas, implement them, and evaluate their performance. In this section, I present the major contributions I have done in TSCH networking. I see these contributions in 4 aspects: TSCH optimizations, TSCH limits, Augmenting TSCH, and Alternatives to TSCH.

TSCH Optimizations

One can imagine countless optimizations to TSCH, the fun part for me is figuring out which of those ideas make sense and really lead to better performance. This process can involve many different tools: analysis, simulation, emulation, simple experimentation, testbed experimentation, or deployments. I think of these techniques purely as tools, and use the one that makes the most sense in a particular situation. In general, I don't see any value in using a complex tool for the sake of using it, if a simpler tool is more appropriate. Because my research is very applied, I end up using an experimental approach most often, compared to for example a complex theoretical model. This again, isn't a critique on complex theoretical models, it is simply that, in many cases, I don't find those to be the right tool.

Channel hopping consists in switching channels to combat multi-path fading and external interference. If we use all available frequencies, I call that "blind" channel hopping. This is used by all commercial implementations I'm aware of, and which can yield 100% reliability even under very high levels of external interference [55]. But if we know some frequencies undergo high level of e.g. interference, why not blacklist those dynamically, and use "**adaptive channel hopping**"? This is the approach we explore in [44] with Branko Kerkez, then PhD student at UC Berkeley. We designed a learning algorithm and showed that, when run on dense connectivity traces, it achieves a Packet Delivery Ratio (PDR) 4.7% higher than blind channel hopping. While this validates our approach, the challenge is to find a practical implementation of it which has a cost lesser than the benefits. Given that such an implementation would involve specific coordination between nodes, the benefits of a complete solution would be at best marginally better than blind channel hopping[5]. We have recently revisited this concept with a team from USC as part of our DIVERSITY associate team [56], without (unfortunately) finding a clear solution.

To stay synchronized, a TSCH network relies on nodes periodically exchanging a short keep-alive message to measure their relative time offset, and correct for it. How often this needs to happen depends on the clock

[5] Proving that the difference between theory and practice is greater in practice than in theory.

drift these nodes experience. Rather than sending a keep-alive periodically, we explore the concept of "**adaptive synchronization**". Nodes track the individual time offset values, and compute their relative drift w.r.t. their neighbor. This allows them to extend the time between two keep alives. We have done similar optimizations, at different times, and on different hardware. With UC Berkeley PhD Student David Stanislowski [57], we showed how adaptive synchronization reduces the minimum achievable duty cycle of an idle network by a factor of 10. More recently, with my Inria post-doc Tengfei Chang [58], we showed how adaptive synchronization allows the nodes in a 3-hop deep network to maintain synchronization within 76 μs of one another, while sending an average of only 18.9 keep-alive packets per hour, a 83% reduction compared to a network not using adaptive synchronization.

How to build the schedule is of course one of the most interesting research topics for a TSCH network. While most of our current work focuses on **decentralized scheduling** (see Chapter 4), our first stab at the problem was with Andrew Tinka, UC Berkeley PhD student [59]. We explored two scheduling algorithms: a purely Aloha-based algorithm which allocates one frequency channel for broadcasting beacons, and a reservation-based algorithm which augments Aloha-based scheduling with a dedicated slot for targeted beacons based on gossip information.

Because TSCH introduces some level of determinism, it is the ideal underlying technology for achieving wire-like reliability. Because wireless is unreliable, any high reliability necessarily comes with link-layer retries. I have explored a number of strategies for achieving this. With UOC Prof. Vilajosana [60], we looked at **packet replication**. This means sending multiple copies of the same application data into the network. As they traverse the network, each copy undergoes different (ideally independent) retries, and having multiple copy increases the overall reliability. We implemented a similar approach in the EWSN 2016 dependability competition [61], but going one step further and sending many copies in a flooding-based approach. This work was done in collaboration with University of Southern California Prof. Krishnamachari (as part of our DIVERSITY associate team).

Great research ideas often lead to increased complexity. For a system to be dependable, usually simpler is better. This is the approach we took with Duquennoy from Swedish Institute of Computer Sciences (SICS) in **Orchestra** [31], a simple yet efficient solution for TSCH networks. In Orchestra, each node schedules one cell to its routing parents by using that parent's MAC address as a key to a hash function. This approach is simple and efficient (we show ¿99.99% end-to-end reliability), but doesn't allow for different report rates for different nodes.

TSCH Limits

There is no free lunch in all of these trade offs. TSCH has its limits, and it's important to get an understanding or what they are.

With Prof. Qin Wang, from the University of Science and Technology in Beijing [62], we focus on the **energy consumption** of a TSCH network. By observing different types of nodes running OpenWSN using an oscilloscope and precision ammeter, we extract the "atomic" energy consumption of each type of timeslot. These measurements are the base for a complete energy consumption model for TSCH.

The goal of UC Berkeley Master student Samual Zats (whom I co-advised) was to study the **scalability** of TSCH networks. Through simulation, we show that a TSCH network can have a density as high as 1 million sensors in a 10 km^2 area, which corresponds approximately to the density of sensors installed in a refinery [63]. We achieve this by scheduling the same set of cells in the TSCH schedule to different pairs of nodes far away from one another.

Augmenting TSCH

The main idea of TSCH is to schedule the communication. We explore different ways of augmenting this basic behavior.

The first one is to compress the data. Unlike a scheme like 6LoWPAN which compacts a header by removing field that are not needed (see Chapter 4), we take a protocol agnostic approach in the MSc work by UC Berkeley Travis Massey (whom I co-advised) [64, 65]. Not unlike zip, we design a **dictionary-based compression** algorithm: once it identifies a pattern of bytes that repeats in subsequent frames, it replaces that with the index of an entry in a dictionary. The dictionnary is built at the same time between the two neighbors, and never needs to be explicitly exchanged. By applying this to real traces of frames being exchanged, we achieve compression ratios between 40% and 80%, yielding predicted energy savings of 30-70% in a typical time-synchronized network.

Label switching is an alternative to explicit routing. In a label switched network, each datagram is attached a label that indicates through which path to go from source to destination. This is a common networking technique in large (wired) networks. With Antoni Morell, from the Open University of Catalunya, we explore how to use it in TSCH network [66]. One elegant concept we develop is how to use a cell in the TSCH schedule on which a node receives a frame as an implicit label. All the node has to do is follow a switching table which links incoming cells to outgoing cells.

Alternatives to TSCH

Of course, TSCH isn't the answer to every problem, and throughout my recent research, I have been exploring alternative techniques.

One is that of **wake-up receivers** [67]. We conducted this study with Richard Su, then a PhD student in the Pister team at UC Berkeley. Rather than agreeing on a schedule and waking up a node's main radio from time to time, a wake-up receiver is a second ultra low-power radio which always stays on looking for a wake-up signal. Once it gets that, it wakes up the main radio. This schemes becomes interesting when the wake-up radio consumes on average less than waking up the main radio periodically.

Together with one of my Inria postdoctoral students Tengfei Chang (and part of the 6TiSCH Inria ADT), we explored **constructive interference**, a technique by which two frames do not collided if they are sent by several device within 500 ns of one another. After developing a very efficient 1114-line long complete implementation [68], we studied how it can be used in TSCH networks.

3.5 Summary

This chapter focuses on the dependability of low-power wireless technology. After defining what we mean by it, we list the challenges a wireless system faces for making it reliable, and focus on external interference and multi-path fading. We then introduce Time Synchronized Channel Hopping (TSCH), a medium access control technique that uses frequency diversity to combat external interference and multi-path fading, resulting in reliable networking. For doing research on TSCH, we created the OpenWSN open-source reference implementation, which we present in this chapter. The last part of the chapter discusses the different research we have been able to conduct around TSCH, on optimizations, limits and other TSCH techniques. Virtually all these studies have been done through collaborations with different institutions, including the University of Southern California (through the Inria-USC DIVERSITY associate team), the Open University of Catalunya, or the University of Science and Technology in Beijing.

Chapter 4

Standardization

In my research, I'm always trying to create technology that "matters". To me, this means designing solutions that answer a real need and are used. One way of achieving this is to push the most promising research ideas through the standardization process.

The goal of standardization is interoperability. It is a way to ensure that two independent implementations "work together". In the low-power wireless context, this means one can buy 50 nodes from vendor A, 20 from vendor B, and they operate in the same solution.

In the majority of the cases, a Standards Development Organization (SDO) develops a standard, a piece of text describing the behavior of an implementation. After the vendor has finished implementing the standard, she verifies her implementation is compliant to the standard by going through a series of compliance tests. Once that works, she can test the interoperability of her product against those of vendor B, which can be done during "interop events".

While SDOs (IETF, IEEE, etc.) are standalone entities, the standards themselves are written by employees of different companies that work together under the umbrella of these SDOs. Participating in the standardization process is a strategic decision for a company; the alternative is to sell proprietary solutions.

4.1 The Standardization Process

When I started hearing about standardization, I thought of a boring process which involves endless and sterile discussions between competitors unwilling to cooperate. I attended my first IETF meeting in San Francisco in 2009, and have been very active in that SDO ever since. My experience couldn't be further than the (very naive) idea I had of it.

Different SDOs have different ways of functioning. On the one hand, the IEEE is very focused on procedure. One has to attend 3 out of the 4 last plenary meetings to have voting rights, and decisions are made by voting. Because that's the only way good standards are made. Or is it? The IETF couldn't be more different in that sense. Attendees can freely participate in any discussion, there is not even any "registration" mechanism. During plenary meetings, decisions are made by judging whether there is "rough consensus" in the room. The process is geared entirely towards the technology, in the hopes of reducing the influence of almost-political lobbying. The interesting thing is that both the IEEE and the IETF, despite their widely different processes, achieve the same goal of being major SDOs for networking.

The influence of both the IEEE and the IETF in the IoT space is enormous. Since 2003, the IEEE has developed the IEEE802.15.4 standard [69], with an extension towards long-range technology in 2012 called IEEE802.15.4g [70, 71, 16, 17, 72, 73, 74, 75, 76, 77, 78]. In 2015, the IEEE integrated TSCH as one of the default MAC layer modes. While I wasn't personally involved in these developments, colleagues of mine at Dust Networks were major contributors to that activity.

Personally, I started following IETF standardization activities when the ROLL working group was formed to design a routing protocol for low-power wireless networks. My first contribution was co-authoring a standard which detailed the requirements on the routing protocol for urban applications [79]. This was done with colleagues of mine at Orange Labs, while I did my PhD in that company. I then co-authored a draft standard which detailed the fundamental principles of what then would become the RPL routing protocol [80, 81, 82, 79, 4, 83]. This was done as part of a collaboration between Cisco, UC Berkeley, Sensinode, and Orange Labs. I had developed some of these principles during my PhD, and saw the power of standardization in transferring research ideas.

4.2 IETF 6TiSCH

My activity at the IETF increased in 2013. While I was working at Dust Networks, we had just released the SmartMesh IP product line a year earlier, and were finalizing integrating its base technology Time Synchronized Channel Hopping (TSCH) into the IEEE802.15.4 standard (that work was eventually published in 2015). Pascal Thubert from Cisco reached out to me and pitched the idea of creating a standardization working group at the IETF, to combine TSCH with IPv6. The IETF had published the 6LoWPAN standard [84, 85, 86, 87], which compacts IPv6 headers, making it more efficient to transport IPv6 on top of constrained IEEE802.15.4 networks.

We created the working group, called "IPv6 over the TSCH mode of IEEE 802.15.4e" (6TiSCH)[1], in October 2013. Pascal Thubert and myself

[1] `https://tools.ietf.org/wg/6tisch/charters`

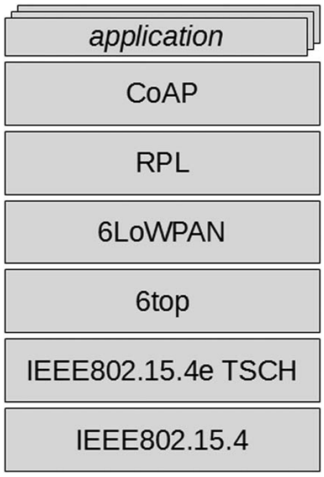


Figure 4.1: The IETF 6TiSCH protocol stack. *Taken from [27].*

are co-chairing the group. The goal of its work is to bring together two technologies in a "best-of-both-worlds" fashion: the industrial performance of TSCH and the ease of use of IPv6.

At the time of writing **421 people** follow the 6TiSCH activities through its mailing-list[2], with a healthy mix of industrial and academic contributors. The 6TiSCH working group has produced 3 RFCs [88, 89, 90], 8 working group documents in the process of being published [91, 92], and various individual submissions. The working group has met 17 times in person, over 100 times through Webex. 6TiSCH has organized 2 plugfests and 5 interop events, each of which attended by 11-15 entities. 6TiSCH is now **supported by all major open-source implementations** (OpenWSN, Contiki[3] [93, 29, 94], RIOT [95], TinyOS), and several companies are building commercial product lines with it. 6TiSCH has been playing the role of catalyst for the academic low-power wireless community, which has now mostly moved towards TSCH/6TiSCH.

While I'm very tempted to get into the technical details of the design of 6TiSCH, discussing why certain architectural decisions were made, I will instead point the interested reader to my Proceedings of the IEEE 2016 and Proceedings of the IEEE 2019 articles [27, 28]. Fig. 4.1 shows the protocol stack that I refer to as the "6TiSCH protocol stack". It consists of existing lower layer standards (IEEE802.15.4, designed by the IEEE), and existing upper layer stack (defined by the IETF working groups 6lo, ROLL and CoRE), glued together by the 6top sublayer from 6TiSCH. This layer terminates the "6top Protocol" which allows two neighbor nodes to add/remove cells to each other's schedule, resulting in distributed dynamic

[2] `https://www.ietf.org/mail-archive/web/6tisch/current/maillist.html`

[3] Contiki-NG, first released mid-2018, is entirely based on 6TiSCH

TSCH schedule management.

One point I want to highlight is that failure is always an option, including in the standardization process. At the beginning of the process, we had been considering a different, much more complicated approach of running the CoAP application protocol inside a link-layer payload. The fact that it sounds like an odd approach is one of the reasons we abandoned that, despite having already defined the sublayer [96], its interface [97], and the packet format [98].

4.3 Research through Standardization

One common misconception (I had) is that standardization is purely a "transfer" activity. That is, after doing some research and getting great results, one would take some time to write a standard as a deliverable of that research. While standardization is certainly "output" for research, it is also a fantastic source of research ideas, and thereby "input" to research. In essence, participating in standardization is very similar to participating in a research community. People present different ideas, meet regularly at standardization events (which play the role of conferences), and write documents and code together. One of the exciting aspects of standardization is that end users of the technology ("industrial people") participate in every aspect of the process. Not only does the process end with a standard document ready for companies to implement and use, the probability of building something that no-one is interested in is very small.

Of course, a researcher participating in standardization activities can write academic papers that summarize the standardization activities. It's a simple way to getting "academic credit" for that activity. This is for example what we did with Maria Rita Palattella from the University of Luxembourg [99], and Prof. Diego Dujovne from Unversity Diego Portales in Santiago, Chile [100], which survey 6TiSCH.

In the remainder of this section, I attempt to show how standardization goes much further than that, and serves as a catalyst for research. I highlight some of the studies around this standardization activities, grouping them into logical blocks.

Evaluation

As the standards evolve a lot during the discussions, SDOs rely on researchers to evaluate the solutions being standardized.

With Oana Iova, then PhD student at the University of Strasbourg [101], we analyze the complex interactions between the IEEE802.15.4 link-layer standard and the RPL routing standard. These haven't been designed for one another, and [101] discusses the possible friction between them. We

Security Level	Software Implementation			Hybrid Implementation			Hardware Implementation		
	TsTx Offset [ms]	TsTx AckDelay [ms]	*minimal* TsSlot Duration [ms]	TsTx Offset [ms]	TsTx AckDelay [ms]	*minimal* TsSlot Duration [ms]	TsTx Offset [ms]	TsTx AckDelay [ms]	*minimal* TsSlot Duration [ms]
no security	1.15	0.67	6.71	1.15	0.67	6.71	1.15	0.67	6.71
MIC-32	2.48	10.07	23.50	1.98	2.24	10.47	1.28	1.12	8.45
MIC-64	2.51	10.19	23.65	2.14	2.36	10.77	1.31	1.19	8.72
MIC-128	2.54	10.31	24.57	2.29	2.45	11.08	1.34	1.25	9.34
ENC	2.31	3.20	16.51	1.77	1.51	9.86	1.28	0.98	8.24
ENC-MIC-32	6.44	14.80	32.35	2.38	2.82	11.44	1.28	1.12	8.45
ENC-MIC-64	6.57	14.86	32.50	2.41	2.94	11.78	1.31	1.19	8.72
ENC-MIC-128	6.60	15.26	33.66	2.44	3.24	12.27	1.34	1.25	9.34

Figure 4.2: Impact of security (implementation) on the minimum TSCH timeslot duration, on the OpenMote-CC2538. *Taken from [104].*

conclude by arguing for a sub-layer between IEEE802.15.4 and RPL, which has become 6top.

With Borja Martinez from the Open University of Catalunya, and Ignasi Vilajosana from company Worldsensing [102], we show how 6TiSCH is suitable for wireless seismic data streaming, specifically because of its synchronized nature.

With Erwan Livolant (part of the Inria-EVA team) [103], we analyze the cost it would take for installing a schedule if 6TiSCH were using a purely centralized approach. This work contributing to use moving to a distributed approach.

One of the most exciting and innovative fields in IoT standardization is security. Since 2016, I have been very involved with it, together with my Inria colleague Malisa Vucinic. Since an important part of dependability is security, it must be addressed heads on. The first challenge is that these devices are constrained in computation power. Given that 6TiSCH mandates the use of link-layer security, we looked with a team from the University of Bari in Italy [104] at the impact link-layer security has on the minimum duration of a timeslot. Fig. 4.2 shows that, on the OpenMote-CC2538, a 10 ms timeslot is perfectly possible provided the proper hardware accelerators for security are used.

After link-layer security, we looked at the secure join process, i.e. how a node that wishes to join a network and the network mutually authenticate [105]. The common wisdom is that DTLS is the way to go, but we showed in [106] that using DTLS yields an unrealistic communication overhead. Both studies were done in collaboration with ST Microelectronics and the University of Grenoble. This participated in 6TiSCH designing the "Constrained Join Protocol" (CoJP), work that Malisa Vucinic is now leading [107, 108, 109, 110].

Scheduling

The crux of the problem, and where a lot of the research challenges lie, is scheduling. Research on scheduling has sparked numerous collaborations, and input from many teams in academia and industry [111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122]. Within the standardization process itself, at least 4 scheduling algorithms have been proposed.

The groundwork was laid by Kazushi Muraoka from NEC corporation, whom I was co-hosting at UC Berkeley. He develops schedule collision detection techniques, which then trigger schedule relocations [123]. This work is then extended by Tengfei Chang, my postdoc at Inria, who proposes a set of metrics which turn the raw collision detection notifications by Muraoka and trigger 6top relocations [124]. Together with Marc Domingo-Prieto from the Open University of Catalunya, we go one step further by considering the decision to add/remove cells as a control problem. We apply a well-know Proportional–Integral–Derivative (PID) controller scheme [125, 126]. Finally, with Maria Rita Palattella from the University fo Luxembourg, we summarize these contributions in creating the On-The-Fly 6TiSCH Scheduling Function [127].

We conducted more long-term research to explore possible avenues.

Together with my postdoc Tengfei Chang, we look at what it would take to achieve the smallest possible latency [128]. Our proposal, the "Low Latency Scheduling Function" (LLSF), cascades cells such that a relaying node can transmit a packet right after it has received it. Using OpenWSN, we show how LLSF yields 82.8% lower end-to-end latency on a 5-hop path than SF0, at no extra costs.

Together with Georgios Papadopoulos from Telecom Bretagne and Pascal Thubert from Cisco, we looked at another way of lowering the latency: sending multiple copies inside the network. The proposal, called "Leapfrog Collaboration" [129] consists in sending two or more copies of the same data into the network, and ensuring they take routes as disjoint as possible. We show, on a Contiki simulation, how the delay and jitter of Leapfrog Collaboration outperforms the default approach of IEEE802.15.4-TSCH by up to 28% and 54%, respectively, while providing high network reliability.

With Malisa Vucinic (then my Inria postdoc), we explored a different aspect of the schedule: the shared "broadcast" cells. These are cells that all nodes listen or transmit on, in a slotted-Aloha fashion. In [130], we make recommendation on how tune the transmission probability on these cells. These recommendations are now part of the 6TiSCH standard.

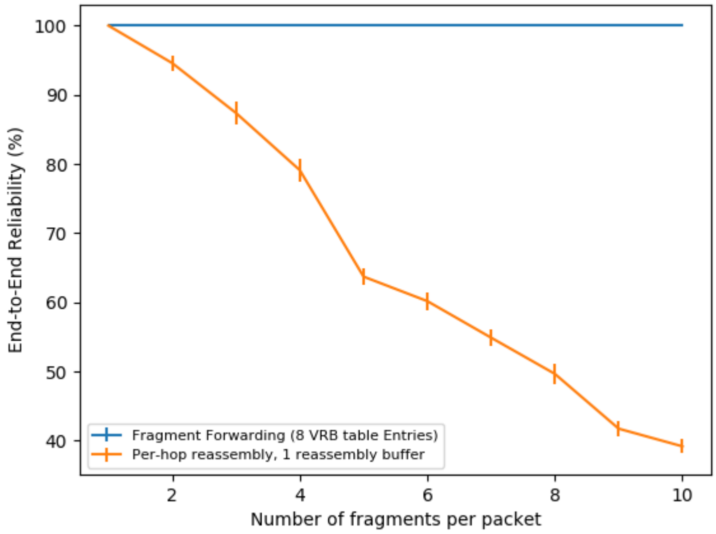


Figure 4.3: Without fragment forwarding, building a reliable network is impossible. *Taken from [131].*

Fragmentation

IEEE802.15.4 networks can carry frames of at most 127 B long, which is very short compared to the maximum transmit unit of IPv6, 1280 B. 6LoWPAN comes with a fragmentation solution, in which a long network-layer packet is cut into possibly many small link-layer fragments, and sent to the next hop that reassembles it. The good news is that this is transparent to the network layer, as the IPv6 implementation is unaware of this fragmentation. Such clean layer separation makes IETFers very happy.

The problem is that it doesn't work. Together with Yasuyuki Tanaka, reseeach engineer at Inria-EVA who I co-advise, we used the 6TiSCH simulator to simulate this behavior [131]. Because the nodes are constrained, they have very limited (RAM) memory space for the reassembly buffer, and can typically only reassemble one packet at a time. In case a fragment from a second packet is received while the first is being reassembled, the node has no choice but to drop one of the two. Fig. 4.3 shows the (catastrophic) end-to-end reliability this yields.

Based on that work, we designed a fragment forwarding strategy [132, 133] together with Carsten Bormann from the University of Bremen. Relay nodes do not reassemble a packet at each hop, but forward it after having changed its tag. As shown in Fig. 4.3, this leads to 100% end-to-end reliability.

Interop Testing

One (obvious) important part of the standardization process is to verify that the standards we write contain enough information for two people to implement it exactly in the same way. If that weren't the case, two vendors could be implementing everything correctly as far as they are concerned, but produce products that don't interoperate.

Throughout the lifetime of 6TiSCH, we have been organizing 2 plugfests and 5 interop events. Plugfests [134, 135] are informal get-togethers of vendors who compare notes and verify basic interoperability. Interop events are more involved, as they involve writing a formal test description, and running through that between each pair of vendors participating in the event. Through the H2020 F-Interop project, we created a methodology and online service to conduct conformance and interoperability tests online [136, 137, 138].

4.4 Summary

This chapter focused on standardization. I start by describing the standardization process, stressing the fact that it is a fun process, and a fantastic generator of collaborations and research ideas. I then describe 6TiSCH, the standardization working group at the IETF which I co-founded and now co-chair. The better half of the chapter is dedicated to presenting the research work I have been conducting around 6TiSCH, for example scheduling or header compression.

Chapter 5

Experimental Evaluation

Experimental evaluation is key to low-power wireless research. Since this field of research is very applied, it is really through experimentation that one can thoroughly validate her ideas. While analysis and simulation are extremely useful, they typically are only a first step towards experimentation. This is very well understood by the research community, and there has been a lot of effort in designing hardware platforms and testbeds, and publishing experimental data.

One of the dilemmas from a purely academic point of view is that it is harder to find a venue (conference, journal) to submit this experimental work to. To be clear, it is in my experience faster to conduct some analysis and simulation and get a paper accepted that presents those results, than it is to do a full experimental campaign (which takes several times more time) and find a venue which accepts a paper which explains that process. Given that the return on investment of experimental work is (again, in my experience) lower than analysis and simulation, there is a tendency by part of the community to focus on the latter. This is entirely understandable.

The problem is that low-power wireless is applied research, and that as in any embedded system, "the devil is in the details". It is therefore very easy to produce purely simulation results which oversimplify the problem and environment, and can lead to false results. One example is fragmentation we presented in Section 4.3. Without modeling the fact that RAM space is limited, one can produce simulation results which show the default scheme yields 100% reliability. As shown in Fig. 4.3, this result doesn't hold when taking into account RAM limitation. Another example is the Unit Disk Graph (UDG) connectivity model used extensively in simulation. UDG is extremely convenient, as it allows a low-power wireless network to be modeled as a pure graph, and therefore allows one to apply graph theory tools to them. While these are extremely powerful tools, they have to be used with the full awareness that the quality of a wireless link is never 100% and that it changes over time and with frequency (see Fig. 3.2). Again, I'm not reducing the merit of UDG-based studies (which I had conducted myself), just underlying the fact that they are a *model* of reality, which represents only a first step in the full qualification of a solution.

I am TPC chair of the workshop on Computer and Networking Experimental Research using Testbeds (CNERT), part of the IEEE INFOCOM flagship conference, which will take place on 29 April 2019 in Paris, France. I am very excited about CNERT, as it is a venue specifically for testbeds and experimental research papers. Given that it is part of one of the most prestigious conferences in the domain, I believe it participates in giving more academic credit to this important type of work.

Over the last years, our community has evolved towards more experimental studies, which I fully agree with. One aspect of that movement is the development of open testbeds which lower the barrier for running implementations at scale (see Section 5.1).

To conclude this introduction, I want to point out that experimentation plays an important role in the standardization activities I highlighted in Chapter 4. During the standardization process itself, the technical contents of a standard evolves a lot as discussions go on within the working group. While the people participating in the standardization activities are absolute experts in their field, it is sometimes hard to know exactly what the performance of a particular proposal is. For a document to become a proposed standard, the IETF requires that there are 2 independent implementations of it, to help prove that (1) the documents are clear enough that they can be implemented and (2) the performance of the standard is good. One good practice the IETF is pushing is to have all documents have "Implement Status" section, at least during the draft phase, which lists the different implementations and their performance, and provides feedback to the working group of the performance of the technology proposed in the document. We have adopted this practice within the 6TiSCH working group.

5.1 Testbeds

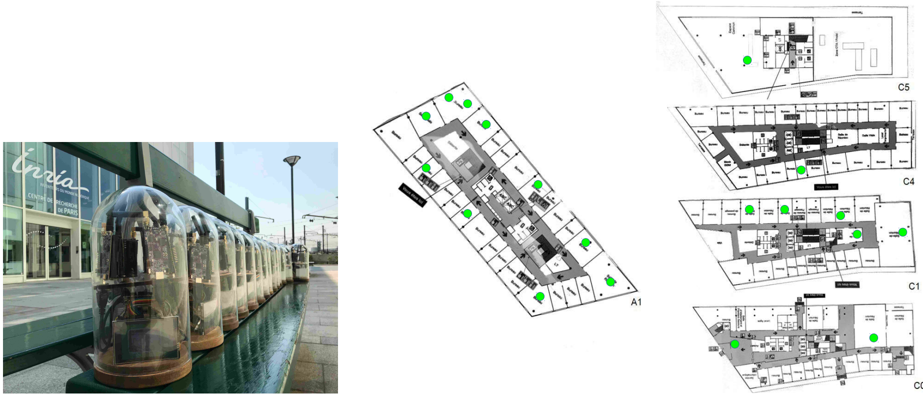
Testbeds are an important tool in the movement of the community towards a more experimental approach [139, 140, 141, 142, 143, 143, 144]. A testbed is a collection of devices deployed in some area, with the infrastructure in place so they can be reserved by an experimenter, and with which the experimenter can assess the performance of her implementation. In the low-power wireless case, in practice a testbed offers the ability to reprogram the devices and interact with their serial port during an experiment. More advanced testbeds offer other services on top of that, including the ability to monitor each device's power consumption, the ability to recompile the code directly on the platform, or to do in-circuit (e.g. JTAG-based) debugging on all platforms during an experiment.

Over the last years, the community has been able to find significant funding to build up these testbeds.

On the French level, the FIT IoT-lab[1] has been the primary testbed in the low-power wireless domain [145, 146]. It consists of over 1,500 nodes deployed at 6 sites across France. A user can request an account, then reserve an arbitrary number of nodes for an arbitrary amount of time to conduct an experiment. Using that account, a user can log into a central Linux machine, in which she can recompile her binary. When an experiment is running, the user has bare-metal access to the low-power wireless devices, and she can load any arbitrary binary on any node. In the back-end, each low-power wireless device is connected to a single-board computer, which itself is wired into the testbed network over a dedicated Ethernet network with Power-over-Ethernet capabilities. The back-end consists of a series of servers, some local to each deployment site, other at the central servers in Paris. The file system of the single-board computers is mapped over NFS to the user's Linux account, resulting in very powerful logging capabilities. The user also has the option of doing in-circuit debugging on each low-power wireless device over JTAG. Moreover, each device is equipped with dedicated hardware to monitor instantaneous power consumption; at the heart of the system is an Analog-to-Digital Converter chip connected to a series resistor. FIT IoT-lab is arguably the most full-featured IoT testbed available today.

FIT IoT-lab is just one example of a testbed. Another is the testbed used by the EWSN dependability competition [147]. The EWSN conference[2] has featured a competition over the past 4 editions, organized by Carlo Boano from TU Graz. This competition has been the catalyst for creating and maintaining a testbed, which is evolving at each edition. We have participated twice in the event, ending at the 4th place both times, but first with an implementation not using constructive interference. The testbed consists of 51 TelosB low-power wireless devices deployed across a building at TU Graz, in Austria. Each mote is connected to a Raspberry Pi which runs the management software. The team has developed an open-hardware interface board between the Raspberry Pi and the mote to monitor energy consumption. The back-end solution consists of a very complete set of services custom-made for the competition. Competitors submit a binary image they have developed outside of the testbed. That image is then loaded into the boards and an experiment runs for a pre-set duration. After the experiment, the testbed outputs the key performance indicators (latency, reliability, power consumption) that are used to rank the competitors. On the European level, the H2020 Fed4FIRE+[3] project federates 17 large testbeds across Europe.

[1] `https://www.iot-lab.info/`
[2] `http://www.ewsn.org/`
[3] `https://www.fed4fire.eu/`



(a) The Inria-Paris OpenTestBed before deployment. 20 domes contain a total of 80 OpenMote B boards.

(b) Location of the OpenTestBed domes within Inria-Paris buildings A and C.

Figure 5.1: The Inria-Paris OpenTestbed. *Taken from [148].*

Together with Prof. Bhaskar Krishnamachari from the University of Southern California, we created the Inria associate team DIVERSITY specifically to look at testbeds. In Krishnamachari's team, I worked mostly with Pedro Henrique Gomes, then PhD student at USC. Prof. Krishnamachari's team has been running the 200-node "TutorNet" testbed at USC. Through that collaboration, we analyzed the state of today's testbeds. My personal analysis is that large institutional testbed tend to be overly complex. Most testbeds rely on dedicated wiring, sometimes requiring Power-over-Ethernet and NFS mapping. This means testbeds require a dedicated Ethernet network to be put up across the deployment site. The direct side-effect of that is that all devices tend to be deployed in a small area – sometimes a single room – with the unfortunate side-effect that the wireless environment is very stable and not generally representative of a deployment done across an entire building. Furthermore, in some cases, because the testbed offers so many services (e.g. JTAG to all boards, power consumption measurement), nodes are custom-made hardware. The unfortunate side-effect is that the low-power devices are not off-the-shelf, so an outside researcher cannot buy a handful of the same boards for local development.

Together with my Inria PhD student Jonathan Muñoz and Fabian Rincon Vija, an MSc intern from ENSTA ParisTech, we explored ways of creating a testbed using a minimalistic approach very complementary to larger institutional testbeds. Our goal was to build a testbed architecture which offers the bare minimum services, and built entirely from (cheap) off-the-shelf components, and can easily be reproduced. The resulting design is the OpenTestbed [148], which is shown in Fig. 5.1a. It consists of a number of glass domes, each containing a Raspberry Pi single-board computer and four OpenMote platforms. Each dome connects to the Internet over WiFi. The software running on each dome connects to an MQTT broker and offers a simple API to load new firmware onto the devices, reset the devices, and interact with their serial port during an experiment. In late 2018, we deployed an 80-node OpenTesbed throughout Inria-Paris (see Fig. 5.1b). The OpenTestbed is now fully integrated within the OpenWSN build routine, i.e. one can build the firmware and load that onto the testbed in a single step. My postdoc Tengfei Chang has been conducting large OpenWSN tests on that testbed since early 2019. Moreover, Brecht Vermeulen from imec in Ghent Belgium, after having seen me present the OpenTesbed at a Fed4FIRE+, has ported the OpenTestbed code to the imec iLab.t w-iLab.t testbed (part of the Fed4FIRE+ project). That testbed now includes the OpenTestbed in the default Linux OS image, so all experimenters use it to interact with their devices during an experiment.

The development of testbeds is in my opinion indicative of the community evolving and focusing more on experimental results. One interesting development of this is the focus on repeatability and benchmarking that has developed in recent years [149, 150]. Results presented in individual papers are often impossible to reproduce, as the source code isn't available, or the procedure isn't explained in enough detail. The authors wants to get their paper accepted; it is therefore natural for them to present the experimental performance results in the most favorable light. The problem is that it is hard to understand the real performance of that solution, and compare that against the performance of another solution. The idea we have been developing since 2016 with a group of low-power wireless academics is that of an open an independent process of benchmarking the performance of solutions [151, 152, 153]. This group of 33 people includes academics from U. Bremen, ETH Zurich, SICS, TU Graz, Bristol U., National U. of Singapore, UC Berkeley, TU Delft, TU Dresden, Chalmers U., Ajou U. Korea, and Inria. This activity has resulted in the creation of the IoT Benchmarks Initiative[4] and the Workshop on Benchmarking Cyber-Physical Systems and Internet of Things (CPS-IoTBench) which has been organized in 2018 and 2019[5].

Much like a third party test lab is used to verify some device doesn't exceed RF radiation regulations, this benchmarking initiative could play the same role. The ultimate vision is to have a automated tool that runs different implementations against the same testbeds, playing the same application scenarios, and making the results public [154, 155]. One embodiment of that vision is the EWSN dependability competition discussed above, in which I participated (but didn't organize). Another is the "6TiSCH Open Data

[4] `https://www.iotbench.ethz.ch/`
[5] `https://cps-iotbench2019.ethz.ch/`

Action" (SODA), a project which aims at publishing real-world performance number of the 6TiSCH protocol stack [156]. That project is lead by Malisa Vucinic and the University of Montenegro. While I don't have any official in it, I help mentoring it. The goal is that a potential end user understands well whether 6TiSCH is appropriate for her application. One important aspect of the SODA project has been to implement the OpenBenchmark set of tools [157]. OpenBenchmark is a cloud-based, reproducible, repeatable and comparable IoT benchmarking service. It facilitates and improves the IoT experimentation workflow: it runs the experiments on supported testbeds, instruments the supported firmware according to the industry-relevant test scenarios, and collects and processes the experiment data to produce Key Performance Indicators (KPIs). At the time of writing, OpenBenchmark[6] supports the OpenWSN implementation running on the FIT IoT-lab and w-iLab.t.

5.2 Beyond Testbeds

The community is moving towards more experimental evaluation, using testbeds. But could we think about moving beyond testbeds?

Simulation tools are powerful at extracting performance fast in a perfectly repeatable way. Within the 6TiSCH work, we have been developing the 6TiSCH simulator [158]. This work is lead by my former PhD student Keoma Brun and research engineer Yasuyuki Tanaka, in collaboration with Steven Latre's team at the University of Antwerp in Belgium. In my experience, the biggest challenge in a low-power wireless simulation platform is designing wireless propagation model used. During a simulation, it is the propagation model that decides, each time a node transmits a frame, which other nodes have received it. To be realistic, the propagation model must capture the behavior of the wireless link, including external interference and multi-path fading. An approach that is commonly taken is to create a model (a series of mathematical formulae, or some state machine) which represents the behavior of the wireless link.

Within my team, we have the luxury of having deployed several networks in the real world (see Chapter 6). This work was lead by my PhD student Keoma Brun-Laguna, through the PEACH SticAmSud project, the REALMS associate team with UC Berkeley, the Inria SmartMarina project, with the support of the France-Berkeley-Fund. We have instrumented these network so they publish network statistics continuously. One of these network statistics is the quality of the connection between each node and its neighbors. We call those "connectivity traces" as they represent the evolution of the connectivity between all pairs of neighbors in each network.

[6] `https://benchmark.6tis.ch/`

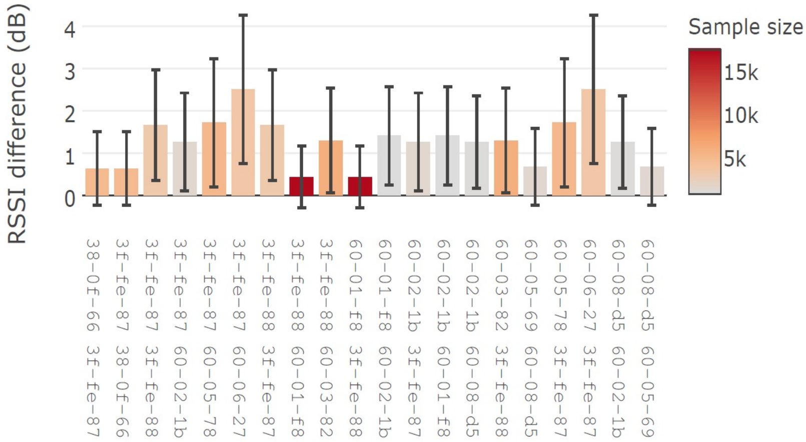


Figure 5.2: Link symmetry. The difference in RSSI between the two directions of 20 wireless links (links continuously active in the 18-25 June 2016 period). The average value is complemented by the standard deviation. The color of the bar indicates sample size. *Taken from [159].*

In parallel, together with my PhD student Keoma Brun-Laguna, we have developed a tool – called Mercator[7] – which allows us to collect similar traces on testbeds. Collecting traces consists in launching an experiment onto the testbed, loading some dedicated firmware on all the nodes and, through a series of scripts, have all nodes transmit bursts of frames in a round-robin fashion while all others are listening. By repeating this procedure over and over, at each available frequency, we generate connectivity traces which are dense in time, frequency and space.

Together with my PhD student Keoma Brun-Laguna, we developed the generic "K7" format[8] to represent those connectivity datasets in a homogeneous way. We made a total of 11 datasets, holding 2,873,156 link quality measurements captured over 170,037 mote-hours of operation, available to the community[9].

These traces contain a goldmine of information and it has been extremely interesting to extract "lessons learnt" from them. What makes that particularly enjoyable is the fact that those results are counter-intuitive.

In our CHANTS'16 paper (part of ACM MobiCom) [159], which we co-authored with colleagues from the University Diego Portales in Chile, and the Open University of Catalunya, we make two of those observations.

First, we observe that links are, in fact, symmetric. This goes against the popular belief that links in a low-power wireless network are widely

[7] `https://github.com/openwsn-berkeley/mercator`
[8] `https://github.com/keomabrun/k7`
[9] `https://github.com/keomabrun/dense_connectivity_datasets`

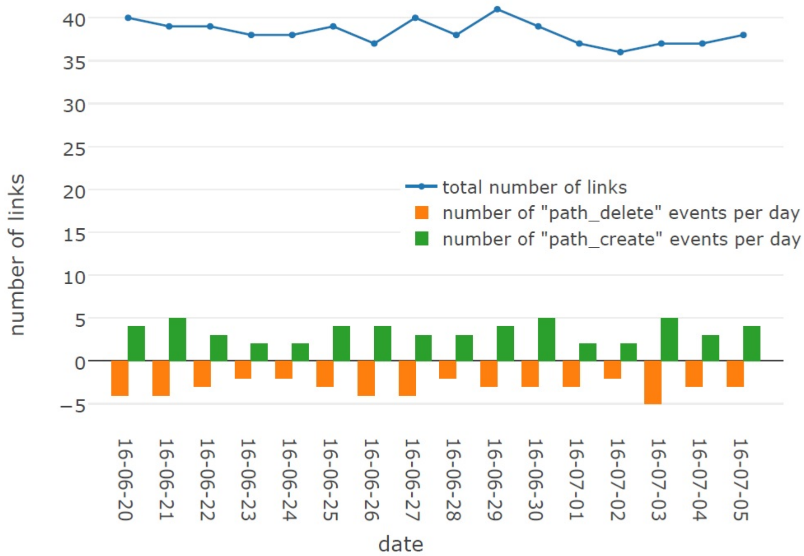


Figure 5.3: Network stability. The number of times a node changes parents per day over a 16-day period. The top portion shows the total number of links. *Taken from [159].*

asymmetric, i.e. that a signal received from node A at node B has a signal strength very different from when node B sends to node A. Entire protocols, such the Optimized Link State Routing Protocol (OLSR), have been designed to filter out asymmetric links. We show in Fig. 5.2 that, when the radios are the same (i.e. they have the same transmit power), the RSSI difference doesn't exceed 3 dB.

Second, we show how channel hopping makes the network extremely stable. Popular belief has it that links in a low-power wireless network continuously "come and go", i.e. that their quality (which can be quantified by its Packet Delivery Ratio, PDR) dramatically swings over time. While this may be true in single-channel solutions, we show in Fig. 5.3 that channel hopping is extremely good at stabilizing this network. Fig. 5.3 shows the number of times nodes change parents in a network deployed in a peach orchard, per day. The number of parent changes (which results in links being added and deleted), never exceeds 5 per day.

After making these observations, we ask ourselves the fundamental question *What makes a deployment "realistic"?* The context is that the community has a tendency to put a lot of faith in results gathered on a testbed. That is, running an experiment on real hardware in a testbed is considered the "ultimate" way of evaluating a protocol. This is somewhat related to the movement of repeatable experimentation lead by the ICube and IRISA labs in France, in which testbeds appear as ideal, as the wireless medium is stable and experiments can be repeated multiple times in pretty much

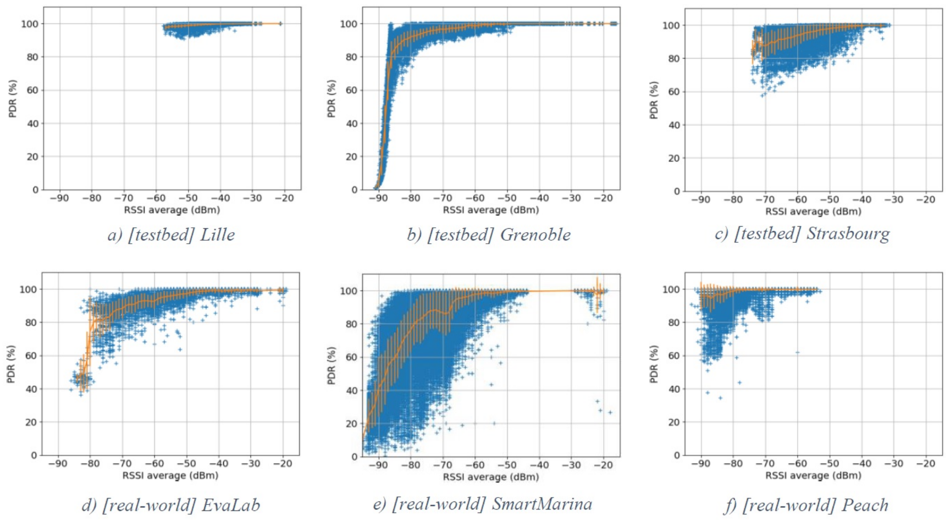


Figure 5.4: Comparing the PDR vs. RSSI "waterfall plots" between testbeds (top) and real-world deployments (bottom). *Taken from [160].*

the same wireless conditions. My argument is that this stability is more detrimental than beneficial. Yes, wireless links in a testbed are in general extremely stable, and so allow for repeatability. But that also makes them unrealistic, as in real-world scenarios, varying level of external interference and multi-path fading makes wireless link very dynamic, on each frequency.

As part of the DIVERSITY associate team between my lab and Prof. Krishnamachari at USC, we develop a tool in [160], called the "waterfall plot", to visualize this dynamism. Fig. 5.4 clearly shows how the waterfall plot of a testbed looks different than that of a real-world deployment (see [160] for a more rigorous analysis).

So, *how can we achieve repeatability?* Together with my PhD student Keoma Brun-Laguna and Yasuyuki Tanaka, a research engineer in my lead whom I co-advise with Pascale Minet, we propose develop "trace-based simulation" [161]. That is, rather than relying on a connectivity model, which can always be criticized, we propose to run simulations on top of connectivity traces. Yasuyuki Tanaka implemented this in the 6TiSCH simulator: when starting a simulation, you load a K7 connectivity trace into the simulator, which "replays" it in lieu of the connectivity model. We believe this is a technique that achieves both realism (you are running a simulation on top of connectivity that was really measured) and repeatability (you can compare the performance of two protocols running on exactly the same connectivity).

5.3 Summary

Together with Chapter 6 describes the work I have been doing on experimental research and testbeds. I start by discussing the importance of experimentation in my field of research, but also highlight the fact that it is sometimes hard to publish. I then describe the different institutional testbeds that have been deployed in the last 5-10 years, and offer a constructive critique about the importance of realistic deployments in those. I introduce the OpenTestbed, which I have developed and deployed with my Inria team, and discuss the benchmarking initiatives I am involved in. Finally, this chapter ends with a discussion about trace-based simulation, a concept I have been developing in collaboration with the University of Southern California, as a win-win solution for achieving realism and repeatability.

Chapter 6

A System-Level Approach

Chapter 5 makes the case for going beyond evaluating solutions in testbeds, and deploying low-power wireless solutions in the real world.

I have driven my Inria team to conduct what I call "system-level research". That is, based on a real-world need, design an end-to-end system, which goes from the sensor to the cloud, and deploy that. This approach is system-level in the sense that it is an entire system. This approach is also cross-disciplinary as the end users of the solution are not low-power wireless experts [162]. And while the sensor-to-cloud solutions we build all include a low-power wireless network, it is just a small part of it.

One question I get asked, especially in France, is whether this is research or engineering. I am always very surprised by this question, and dedicate this chapter to answering it. My argument is that this system-level approach is the ideal approach for generating an explosion of research that is both relevant and high-risk-high-gain in nature, and that, by throwing you in the deep end of the pool, bursts the low-power wireless academic bubble we are so easily trapped in.

I have been involved in research on low-power wireless networking since 2005, and have witnessed and participated in the community of generations of researchers producing countless studies on every aspect of the problem. And it has totally paid off. The technology developed by our community has now been standardized, and companies have products on the market that offer wire-like reliability, security and years of battery lifetime. This absolutely doesn't mean that this is a solved field, on the contrary, it opens up even more areas to explore, see Chapter 7. But it means that we have now low-power wireless networks that work. So let's use them.

My approach has been to actively seek out entities that have a problem that can be solved using low-power wireless networks, and work with them to build a Minimal Viable Product (MVP). For them, we operate almost like a startup that delivers a product. But for us, the low-power wireless researchers, this is "just" a vehicle to conduct our research, which has three major advantages. First, it allows us to test our systems. We think we did all the analysis, simulation and testbed evaluation right, but will the network work in the field? Second, it allows us to do cross-disciplinary research, which usually involves the analysis of the sensor data. It forces us to "move up" from the details of the network to extract meaningful information from the data it generates. Third, and most importantly, it is an ideal way for making ourselves entirely vulnerable to new research ideas. Every aspect of a deployment triggers new questions, forces us to reassess our hypothesis, and usually shows that many assumptions we had were plain wrong. And each of these points triggers new research. Section 6.2 shows numerous examples of this type of research.

Personally, I have always tremendously enjoyed going into the field, deploying sensors and making things work, so my statements above are definitely influenced by this inclination. The final demonstration of my PhD involved a remote controlled airplane equipped with a low-power wireless devices collecting data from a field of devices [163].

When joining Inria, I set up an associate team (called REALMS [164]) with Profs. Glaser and Pister at UC Berkeley and Prof. Kerkez at U. Michigan, to be able to conduct this type of research. I am the lead of that associate team, and coordinate the visits between France and the US. The collaboration has run since 2015, and has resulted in 8 trips from France to the US, and 11 from the US to France. While I don't have an official affiliation with UC Berkeley, I have been mentoring the following PhD students specifically, in particular when preparing papers: Carlos Oroza, Sami Malek, Ziran Zhang. I hired Ziran Zhang on a 16 month postdoc position right after he graduated from the UC Berkeley team.

In 2016, I also set up a a second associate team, called DIVERSITY, with Prof. Bhaskar Krishnamachari's team at the University of Southern California. This associate team has resulted in 2 trips from France to the US, and 2 trips from the US to France. While I don't have an official affiliation at USC, I have been mentoring PhD student Pedro H. Gomes. I hired Gowri Sankar on a 16 month postdoc position right after he graduated from the USC team, but he could not accept the offer.

6.1 Real-World Deployments

In this section, I present the 5 projects I have been involved in since 2016, in which we deploy low-power wireless networks for specific applications.

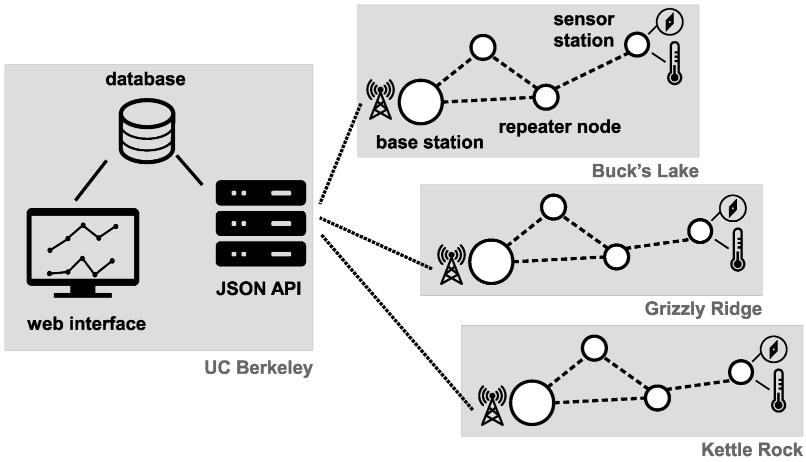


Figure 6.1: The SolSystem architecture, as used in the SnowHow project. *Taken from [165].*

SolSystem

SolSystem[1] isn't a deployment, but rather the back-end solution we have developed and which is used by all deployments described below. It consists of the following elements, from right to left in Fig. 6.1:

- motes are equipped with sensors and run customer firmware that reads those sensors periodically. We use the LTC5800 chip as the main micro-controller and radio, which we program using IAR, based on Analog Devices' On-Chip SDK[2].

- a gateway connects the low-power wireless mesh network to the Internet. Depending on the deployment, that can be over Ethernet (SmartMarina), WiFi (SaveThePeaches), cellular or satellite (SnowHow).

- a server terminates a JSON API (written in Python) which sends the data into an InfluxDB database. A Grafana interface displays the data on a browser in real time. Pieces of the central server run on dedicated machines (at Inria and UC Berkeley), the remainder in the IBM Cloud.

The low-power wireless protocol I use in SolSystem is SmartMesh IP, which can be seen as an early version of the 6TiSCH protocol stack. SmartMesh IP is an extremely flexible networking solution, in which a network can contain up to 50,000 nodes and many Access Points. In our deployments, we never exceed 100 motes per Access Point, which allows us to use the simpler

[1] `www.solsystem.io`
[2] `www.dustcloud.org`

"embedded manager" solution of SmartMesh IP. In this configuration, the manager software runs entirely on the micro-controller of the access point. The network can generated up to 36 packets per second, each containing up to 90 B of application payload. SmartMesh IP allows one to trade-off latency and throughput for power consumption. In the trade-off point I operate the networks in these deployments, latency in typically in the 2-4 s range (from the mote to the manager) and power consumption most often below 50 uA at 3.6 V (translating to over a decade of lifetime of 2 AA batteries). SmartMesh IP has been absolutely flawless for these deployments, which is very important as it allows me to focus on the rest of the projects.

At the heart of SmartMesh IP is the IEEE802.15.4e Time Synchronized Channel Hopping. All nodes in a SmartMesh IP network are synchronized, with a synchronization error not exceeding 15 us. Time is cut into timeslots which are 7.25 ms long. A communication schedule orchestrates all of the communication in a SmartMesh IP network. That schedule indicates to each node what to do in each of the timeslots: transmit, listen, or sleep. The schedule is continuously updated to adapt to changes in the amount of data each node is producing, or to react to topological changes. By default, each node has 2 routing parents, which means the network stayed perfectly formed even when switching of nodes during operation. A SmartMesh IP network offers over 99.999% end-to-end reliability.

SmartMesh IP is a commercial product, *not* the result of research done in my team at Inria. It is, however, the result of my personal work at Dust Network, as I was part of the systems team that designed it and I have implemented part of it. SmartMesh IP is not an academic research project, and contains lots of intellectual property which makes it perform better than other solutions on the market, and which is not public information. And while I don't have any "academic credit" for my work on SmartMesh IP, I have the personal scientific satisfaction of knowing exactly how it works. That being said, we have published a number of papers about SmartMesh IP. Together with colleagues from Dust Networks, we published [34] and [35] which give an overview of the capabilities of SmartMesh IP for an end user's point of view. Together with my MSc intern Marcelo Ferreira and my PhD student Jonathan Munoz, we show in [36] that the range of a SmartMesh IP node is 1.3 km in line-of-sight conditions.

We configure the nodes to generate sensor data periodically, with a period between 30 s and 15 min. On top of sensor data, the network also reports network statistics every 5 min. These network statistics contain a plethora of information including:

- Counters local to the mote generating them. This includes the number of data packets it generated, or the amount of charge it has already consumed.

- Statistics on the links that each mote is using, to each of its neighbors. This includes counters for the number of frames transmitted, and frames for which it received an acknowledgment. This is helpful to assess the overall stability of the network.

- Statistics on the neighbors each node hears but isn't communicating with. This includes the address of the node it hears, the number of frames it receives from it, and their average RSSI. This is helpful to assess whether the network is deployed densely enough to form a good mesh.
- "background noise" measurements for each of the frequencies when the node isn't scheduled to receive any data. This allows us to build a heat map of interference, resulting in a "distributed spectrum analyzer".

In some deployments, these statistics account for 90% of the data generated by the network, i.e. a network generates $10\times$ more statistics than sensor measurements. Collecting and analyzing these statistics is one of our main returns on investment for these deployments.

To represent these different types of sensor data and network statistics, we developed the "Sensor Object Library" (SOL) which represents each type of sensor data as a generalized Type-Length-Value tuple [166]. SOL comes with a repository of types, and Python and C implementations which handle serialization/deserialization of these objects between binary to JSON. The SOL library is running on the motes, the gateway and the server. The database stores time series of SOL objects.

SOL is just a data representation, which can be carried over any transport or application protocol, including CoAP. In our deployment, we carry SOL objects directly over UDP. SOL is developed together with Prof. Glaser's team at UC Berkeley and Prof. Kerkez' team a UMichigan, as part of the Inria associate team REALMS. The source code is available under a BSD open-source license in three main repositories (`sol`, `solmanager`, `solserver`) under `https://github.com/realms-team`. I am the designer of SOL and kickstarted its implementation. Keoma Brun-Laguna, my former PhD student and associate in the Falco startup, is now the maintainer of that code.

SavethePeaches

The SaveThePeaches[3] project is a STIC AmSud collaboration between Inria in Paris, Universidad Diego Portales in Chile, Universidad Technologica Nacional in Argentina and the INTA research institute in agronomy of Argentina, which ran in 2016-2017. I co-wrote the proposal and was the Principal Investigator (PI) on the French side. My PhD student Keoma Brun-Laguna was the main other person of my team involved. From a technical point of view, my team provided the low-power wireless solution, which

[3] `www.savethepeaches.com`, `https://youtu.be/_qGSH8l0Vkk`

involves the low-power wireless network and the back-end (which use SolSystem) and the firmware that runs on the motes and interface to the sensors. Personally, I designed the solution and implemented the approximately 80% of the solution deployed.

The goal of the SaveThePeaches is to develop a frost detection solution [167, 168]. In any fruit orchard, in the Spring when the flowers bloom and it is still cold, there is a risk that it gets too cold at night and that the flowers freeze and fall, preventing them from eventually turning into fruit [169, 170, 171]. In the Mendoza region in Western Argentina in 2013, because of 4 particularly cold nights in September (their Spring), peach producers lost 85% of their production, which accounts for USD 10 million and 10,000 jobs [172, 173].

If the producer can know a couple of hours in advance that a frost event is coming, she can get a team to install heaters throughout the orchard, and in the worst case fly a helicopter to push the hot air down. This is a very well-known technique that is carried out routinely [12, 174], but it takes a couple of hours to put in place. The problem is hence not to fight the frost event, the challenge is to predict it.

The SaveThePeaches project uses a network of air temperature and air relative humidity, soil moisture and soil humidity sensors deployed across a 5000 m^2 peach orchard in Mendoza, Argentina. The network consists of 23 battery powered motes deployed on top of 5 m high poles, connected over a wire to 4 SHT31 sensors deployed at different levels along the pole. The gateway of the network is located 400 m away, next to a building where there is power and Internet connectivity.

The network has been running continuously since its installation in May 2016. The sensor data is being analyzed by the INTA research institute in agronomy to predict frost events. This work has resulted in 3 joint journal articles [167, 175, 176] and 2 joint conference papers [159, 168].

SnowHow

SnowHow[4] is the technical project that stems out of the REALMS associate team I have set up between my team at Inria, Prof. Glaser at UC Berkeley and Prof. Kerkez at the University of Michigan, which has been running since 2015. I lead the writing of the protocol and now coordinate the trips between our teams (8 trips from France to the US, 11 from the US to France). Technically I have designed the back-end solution (based on SolSystem) and implemented 80% of it. My PhD student Keoma Brun-Laguna has written the firmware that goes onto the micro-controllers, where I have served a SmartMesh IP expert (as the software development kit Keoma has been using is something I created while at Dust Networks). SnowHow is a small

[4] `www.snowhow.io`, `https://youtu.be/dOoE1xtViZs`

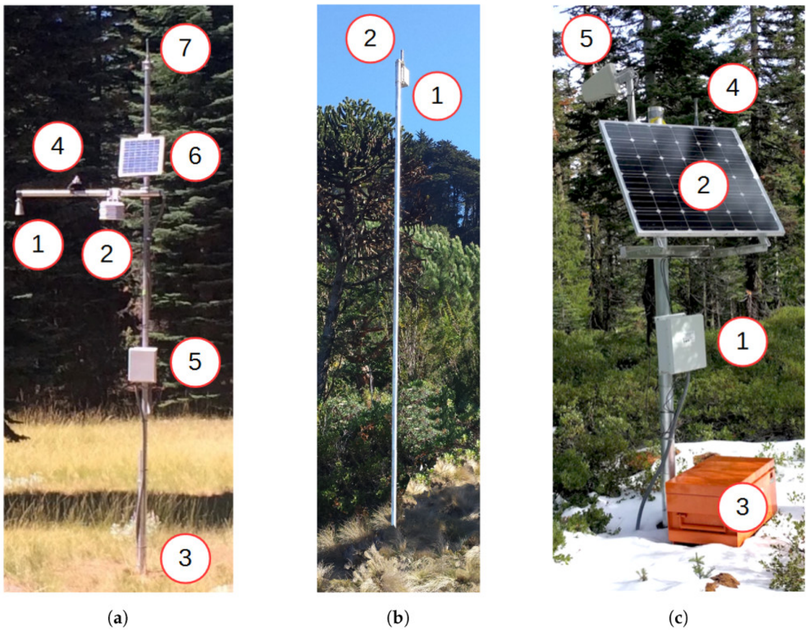


Figure 6.2: Hardware used in the SnowHow Deployments. (a) sensor station, (b) repeater node, (c) base-station. *Taken from [165].*

part of a large NSF project to monitoring the snowpack on the California Sierra Nevada to better understand the state's water problem [177, 178, 165]. The bulk of the SnowHow project is carried out by UC Berkeley Prof. Steven Glaser's team, with contributions from my team on the networking side.

A SnowHow deployment consists of approximately 50 devices deployed in a 1 km^2 area: sensor stations, repeater nodes and a base-station (see Fig. 6.2). The sensor station contains snow depth, temperature, humidity, soil moisture, soil temperature and solar radiation sensors. These are connected over wires to a low-power module. The base-station collects the data of the sensor network and forwards it over cellular or satellite to the cloud, using SolSystem. There are 21 SnowHow networks deployed, for a total of 945 sensors. Fig. 6.3 shows the different view of the SolSystem back-end, for a deployment called "Buck's Lake".

Each of these sensors produces a sensor measurements every 15 min. These are received at stored at a SolSystem-enabled server at UC Berkeley and summaries are published monthly to the community of hydrologists of the state of California. This allows them to better model the snowpack and thereby understand the water problems the state of California has endured. While I am not involved in the exploitation of the sensor data, I am heavily involved in exploiting the network statistics the networks are generating. A network generates approximately 10 times more network statistics than sensor measurements. Section 6.2 details the work we have been able to do

(a) (b) (c)

Figure 6.3: The SnowHow networks. (a) logical view of the topology, (b) location of the nodes, (c) sensor data received live from the field. *Taken from [165].*

on these datasets.

This collaboration has resulted in 3 joint journal articles [177, 179, 165] and 2 joint conference papers [166, 178].

SmartMarina & FALCO

SmartMarina[5] was a research project which studied the feasibility of using low-power wireless sensing technology for monitoring a marina. This project was conducted in collaboration with SODEAL, the company running the Cap d'Agde marina in Southern France. Cap d'Agde is the third largest marina in Europe, with up to 4,100 boats in peak season. SmartMarina was supported by Inria-SiliconValley, who funded the salary of the Ziran Zhang, the postdoc who joined my team after graduating from UC Berkeley, and whom I supervised. The project was awarded additional funding from the prestigious France-Berkeley-Fund. I lead the proposal to Inria-SiliconValley and the France-Berkeley-Fund, then lead the project and supervised the postdoctoral research lead.

We developed an end-to-end marina management solution which involved deploying approximately 50 sensors in the Cap d'Agde marina. Motes were deployed under the pontoons and in electrical boxes to monitor the presence of the boats in the different moorings, and their consumption of electricity. The final user of the data is the operator of the marina.

Together with 4 associates, including my previous PhD student Keoma Brun-Laguna, we created the spin-off company Falco[6], which was officially "born" on 14 January 2019. Falco is a complete marina management solution which builds on the SmartMarina research projects. Because of the

[5] `www.smartmarina.org`, `https://youtu.be/LUcLE8DORbM`

[6] `www.wefalco.fr`, `https://youtu.be/35HdoFLrCf0`

dataset name	# nodes	duration	# PDR measurements
`lille_1`	5 nodes	15 days	367,293
`lille_2`	50 nodes	18 h	274,392
`grenoble_2`	50 nodes	18 h	284,068
`strasbourg_1`	5 nodes	3 days	81,900
`strasbourg_3`	49 nodes	21 h	300,938
`evalab_1`	22 nodes	3 days	9,422
`evalab_2`	22 nodes	3 days	58,895
`smartmarina_1`	18 nodes	4 months	1,122,177
`smartmarina_2`	19 nodes	4 months	183,939
`peach_1`	19 nodes	4 months	166,927
`inria-c`	20 nodes	30 h	23,205
11 datasets	**170,037 mote-hours of operation**		**2,873,156 PDR measurements**

Table 6.1: Summary of the published datasets. *Reproduced from [160].*

intellectual property involved, I'm not at liberty to describe the technology in more detail than to say it is based on SolSystem and SmartMesh IP.

6.2 An Explosion of Research Needs & Ideas

The projects listed in Section 6.1 have allowed us to work with other 1,000 sensors deployed on 3 continents. Each deployment has been running for over a year, generating sensor measurements which domain experts are analyzing [176, 180, 181, 182, 183, 184]. I want to focus in this section on the data which is more important for me: the network statistics. Together with the connectivity data we collect on testbeds using our Mercator tool (see Section 5.2) we have assembled what I believe is the largest connectivity dataset for frequency-agile low-power wireless networks in the world. We have made the most relevant portions of that data freely available to the community[7]; Table 6.1 summarizes what these datasets contain.

These datasets contain a goldmine of data waiting to be analyzed. In the remainder of this section, I highlight some of the research that was conducted thanks to these deployments.

Having connectivity datasets gathered on both testbeds and real-world deployments is a unique opportunity to compare them. In Section 5.2, I discussed the not so intuitive results obtained from exactly that exercise. Together with my PhD student Keoma Brun-Laguna and Pedro Henrique Gomes from USC (through our DIVERSITY associate team), we further de-

[7] `https://github.com/keomabrun/dense_connectivity_datasets`

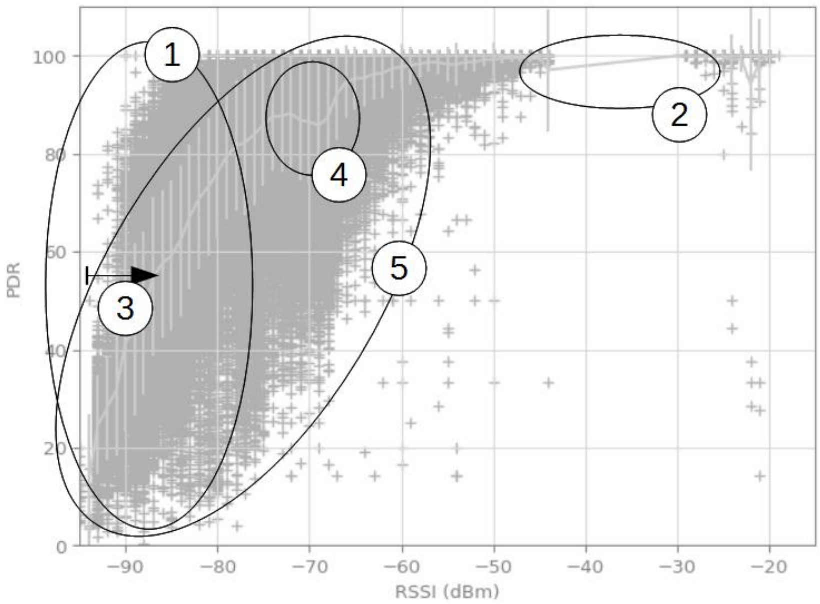


Figure 6.4: Five elements to look at when assessing the connectivity in a deployment by "reading" its waterfall plot. *Taken from [160].*

velop a methodology that assesses which wireless phenomena are present in a deployment [160, 175]. One use case is to see whether a testbed deployment is representative for some of these wireless effects. The approach consist in analyzing the "waterfall plot" extracted from a particular deployment, i.e. a scatterplot of PDR as a function of RSSI. In the absence of external interference and multi-path fading, the waterfall plot is at PDR=0% approximately 10-15 dB below the radio chip's sensitivity, and at PDR close to 100% above sensitivity, with an almost linear ramp between the two. Please note that there is significant multi-path fading and external interference in Fig. 5.4, which explains why the waterfall plot is shifted to the right (as the sensitivity of the LTC5800 is -93 dBm).

Fig. 6.4 shows the waterfall plot from the SmartMarina. Each cross represents a PDR measurement; the mean value with standard deviation is also depicted. Fig. 6.4 contains annotations on how to "read" it:

- Make sure the left-hand side of the waterfall plot is complete, i.e. it reaches PDR=0%. Not having this left-hand side indicates that your nodes are very close to one another. On a testbed, this means you are not testing your solution close to sensitivity.
- Any discontinuity in the plot indicates that your deployment contains either very good links, or bad links, but no in-between. This is typically the case for networks in which nodes are deployed in clusters.

- A waterfall plot shifted to the right (taken the radio's sensitivity as a reference) indicates the presence of external interference and multi-path fading.
- A "dip" in the waterfall plot indicates strong interference on specific links.
- The spread of PDR measurements around the mean value indicates dynamics in the environment.

Given these rules, just looking at a waterfall plot allows one to determine how close together nodes are deployed, and whether external interference, multi-path fading and dynamics are present. We showed the waterfall plots for 3 testbeds and 3 deployments in Fig. 5.4. The rules above allow us to get good insights into the connectivity in the deployments (numbers refer to the rules above). The IoT-Lab Lille and Strasbourg testbeds[8] suffer from the fact that nodes are deployed too close to one another (1). Nodes are deployed in clusters in SmartMarina, as shown by the discontinuity in the plot (2). The fact that the EvaLab and SmartMarina waterfall plot are shifted right compared to Peach indicates external interference in the former two, very little in the latter (3). A Wi-Fi camera interferes with a small number of links in SmartMarina; this can be seen by the "dip" in the plot (4). Nodes in the IoT-Lab Grenoble testbed are deployed far enough apart from each other, but lacks dynamics in the environment (5). The rules described above are simply observational; we are working on a tool to quantify these different aspects.

Together with Carlos Oroza, PhD student at UC Berkeley who I have co-advised on this aspect as part of our REALMS associate team, we used these datasets to take a fresh look at connectivity models. We let the SnowHow networks run for 1 year, after which we had gathered 42,157,324 RSSI samples collected from the 2218 links in the networks [179]. These networks are all deployed in a pretty homogeneous 2000 km^2 forested area. We are looking to predict the connectivity in such a network. The literature points us to well-known canonical model (free space, plane earth), and empirical propagation models (Weissberger, ITU-R, COST235) which were specifically designed for predicting connectivity in exactly these types of forested areas[9]. The first fun result is to plot the predictions of the different models against the dataset we gathered. What Fig. 6.5 shows is that all the models make different predictions, which are all different from the measurements we actually take.

[8] I am aware that both testbeds have recently undergone reorganization and extensions, and am looking forward to repeating this study and doing a before/after comparison.

[9] I am now aware of other models, including [185] which we could have compared against, and will when we revisit this work.

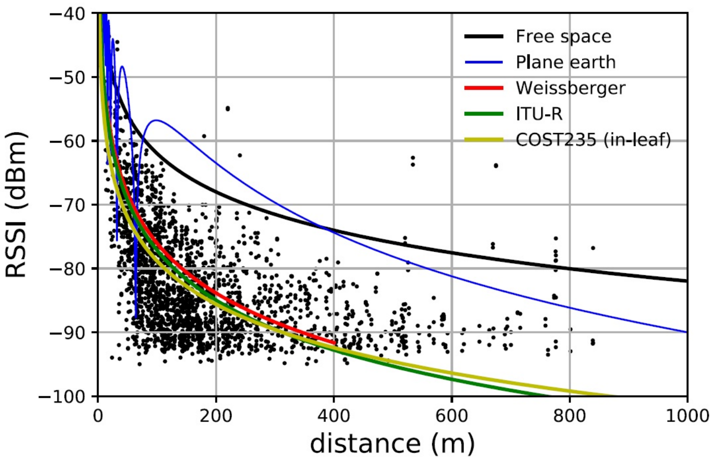


Figure 6.5: Comparing the different canonical and empirical propagation models (lines) against the 42,157,324 RSSI samples collected.

So rather than using expertise to turn empirical connectivity observations into some equation, let's take a hands-off approach and let a machine learning algorithm design such a model for us. We start by annotating the samples with features such as distance between nodes, canopy coverage, terrain variability, and path angle. We then feed that data into four candidate machine-learning algorithms (Random Forest, AdaBoost, Neural Networks, K-Nearest-Neighbors). Out of those, Random Forest yields the lowest error. Fig. 6.6 is to me unbelievably revealing, as it shows that our machine-learning approach outperforms all of the previously published models. It achieves a 37% reduction in the average prediction error compared to COST235, the canonical/empirical model with the best performance.

Random Forest allows one to further see which features impact the model the most. The canonical/empirical models, apart from some very coarse parametrization, only consider the distance between two nodes when calculating the RSSI. Fig. 6.7 shows that, in our model, 53% of the decision making in the model is done based on features that are *not* distance.

6.3 An Exciting Teaching Vehicle

Embedded systems are the perfect teaching tool. They offer infinite opportunities to let student "see for themselves". And adding connectivity to it (low-power wireless for example) allows the students to build very complex chains of information. In the most complete case, information goes from a physical sensor to a micro-controller, through a low-power wireless mesh network, to a gateway, to a single-board computer, to a cloud-based backend system, to a database, and to the student's browser. Being able to build

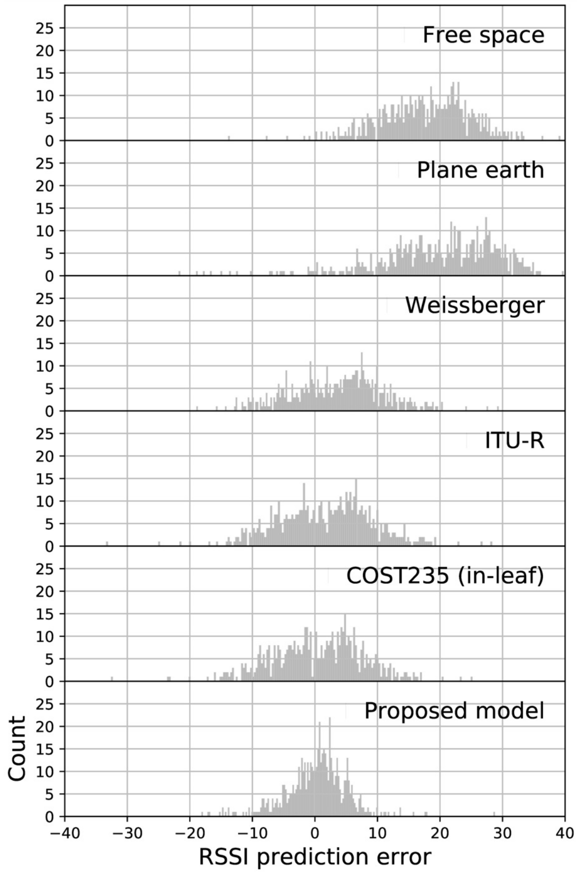


Figure 6.6: Distribution of errors under canonical and empirical models (top panels), compared to proposed model (bottom panel) for year-averaged RSSI data.

Feature	Mean importance	SD importance
Path ground distance	0.47	0.10
Terrain complexity	0.15	0.08
Vegetation variability	0.10	0.04
Mean percent canopy	0.09	0.02
Path angle	0.08	0.03
Source canopy	0.05	0.01
Receiver canopy	0.05	0.01

Figure 6.7: Independent variable importance inferred from the random forest algorithm, mean and standard deviation.

Figure 6.8: The April 2018 promotion from ENSTA ParisTech that took the Dust Academy course.

up this entire chain fast and with relatively simple components is both incredibly motivating for the students ("The dial is moving on my phone!", "I can control my fan remotely!"), and offers the instructor infinite possibilities to dig into any topic, from SPI buses to RTOS priority inversion, embedded protocols or web interaction. Given that perspective, my first guiding principle when teaching is to build real things.

One of the things I see when interviewing people is that students are often not exposed to the technology being used in real-world applications. They have often some experience with open-source projects, development boards and DIY hardware. And while these tools are perfectly valid, they don't convey to the student a clear picture of what the state of the art is. Given that perspective, my second guiding principle when teaching is to use technology that is really out there.

In that spirit, I have been developing the "Dust Academy" [186] teaching material around the SmartMesh IP product line, and putting all the content online[10]. The course consists of 40% of theory and 40% of hands-on practice (deploy networks, attach sensor/actuators, build a back-end system). The final 20% consist of a project in which students instrument their building for the duration of the course, and implement smart building applications they have come up themselves. I have taught the Dust Academy 17 times, in different formats, to undergraduate students (Fig. 6.8), researchers and end users of the Smartmesh IP product line, from a 2 h crash course to a 6 week module. I taught the Dust Academy material at ENSTA ParisTech (together with other instructors, including Prof. Benoit Geller and Tarak

[10] `https://dustcloud.atlassian.net/wiki/spaces/ALLDOC/pages/40468511/Dust+Academy`

Arbi), Telecome ParisTech, University College London, UC Berkeley, and University of Southern California.

6.4 Summary

This chapter focuses on the system-level approach I have taken. I start by describing what I mean by a system-level approach, and how it allow me to test the systems we design, conduct cross-disciplinary research and make ourselves vulnerable to new research ideas. I then describe the SolSystem end-to-end architecture, which involves a SmartMesh IP low-power wireless network connected to a back-end system, using a compressed data representation which I designed called SOL. I then provide details about the deployments done: SavethePeaches (a frost event detection solution deployed in Argentina, SnowHow (snowpack monitor networks deployed in California) and SmartMarina (smart parking for boards deployed in France). These deployments include over 1,000 sensors deployed on 3 continents. SmartMarina has resulted in the creation of the FALCO startup company. The second half of this chapter focuses on the research resulting from these deployments, based in the most part on the analysis of the connectivity datasets collected in the deployments. Together with my Inria team and mainly through collaboration with UC Berkeley (REALMS associate team) and the University of Southern California (DIVERSITY associate team), we conducted research on tools for comparing connectivity between real-world deployments and testbeds, and a machine-learning based connectivity model. This chapter ends by presenting the Dust Academy, a teaching vehicle based on SolSystem.

Chapter 7

Summary and Road Ahead

7.1 Overall Summary

It is an exciting time to be working on research and development of Internet of Things technology. Throughout this manuscript, I hope to have been able to give a comprehensive overview of the research I have been doing since my PhD. This research has been organized around 4 themes.

End users are asking for networks on which they can depend. They “just” need a low-power wireless network which delivers all of their data, fast, and that they don’t need to change batteries too often. Yet, building a dependable network is hard, as its reliability is challenged by two wireless phenomena: external interference and multi-path fading. Time Synchronized Channel Hopping (TSCH) is MAC-level technique with efficiently combats those, while keeping the power consumption of the nodes very low. Through our open-source implementation, OpenWSN, we have been able to study several aspects of TSCH, including TSCH optimizations, TSCH limits, new techniques that augment TSCH, and alternatives to TSCH.

Standardization is an exciting process which participates in transferring research project into well defined interoperable technology companies can use. With the IETF, we have created the 6TiSCH working group to standardize a protocol stack for the industrial IoT which combines the performance of TSCH with the ease of use of IPv6. Standardization is far from being just an outcome of research, it is a formidable generator of research, including on evaluating the standards being written, and augmenting them. In the context of TSCH, this has enabled us to work on scheduling, fragmentation and interop testing.

In a research field as applied a low-power wireless networking, experimental evaluation of the technology is immensely important. There has been a general movement of the field towards experimentation, and different team have brought up institutional testbeds. A research can use those to run her implementation at scale and verify the correct behavior of her code. As any tool, it is important for testbed users to understand what its limits are, including on the realism of its wireless connectivity. We are proposing to couple testbeds and real-world deployments with simulations by evaluating low-power wireless network software on a simulator that replays previously-recorded connectivity traces.

I argue that, now that our research community has created low-power wireless technology that works, let's use it to solve real-world problems and adopt a system-level approach. The return on investment for me in creating and deploying these sensor-to-cloud solutions has been to collect vast amounts of network statistics. These have given us some unique view into these networks, including approaching connectivity prediction using machine learning rather than modeling.

The more low-power wireless technology evolves, the more potential it creates, including for research. In the following sections, I highlight three high-Risk-High-Gain research avenues, which I plan on addressing. I order them from short term to long term.

7.2 (short term) Agile Networking

Today's low-power wireless devices typically consist of a micro-controller and a radio. The most commonly used radios are IEEE802.15.4 2.4 GHz, IEEE802.15.4g sub-GHz and LoRA (SemTech) compliant. Radios offer a different trade-off between range and data-rate, given some energy budget [187, 188, 189, 190, 191, 192]. To make things more complex, standards such IEEE802.15.4g include different modulations schemes (2-FSK, 4-FSK, O-QPSK, OFDM), further expanding the number of options [193].

"Agile Networking" is the concept I am developing which redefines a low-power wireless device as having *multiple* radios, which it can possibly use at the same time. That is, in a TSCH context, for each frame a node sends, it can change the radio it is using, and its setting. If the next hop is close, it sends the frame at a fast data rate, thereby reducing the radio on-time and the energy consumption. If the next hop is far, it uses a slower data rate.

The first challenge was hardware support. With our input, the OpenMote company designed the OpenMote B (Fig. 1.2), which contains both a CC2538 IEEE802.15.4 radio, and an AT86RF215 IEEE802.15.4g radio, offering communication on both 2.4 GHz and sub-GHz frequency bands, 4 modulation schemes, and data rates from 50 kbps to 800 kbps.

The second challenge is to redesign the protocol stack in a standards-compliant way. We are working on a 6TiSCH design in which neighbor discovery happens independently on each radio, and the same neighbor node can appear as many times in the neighbor table as it has radios. The goal is to standardize an "Agile 6TiSCH" profile, without having to touch

Figure 7.1: A stabilized inverted pendulum in which sensor and actuator communicate over a 3-hop OpenWSN network (full state controller, 150 ms critical delay).

the core specifications. Jonathan Munoz has co-authored an Internet Draft which details the impact agile networking has on the IETF 6TiSCH protocol stack [194].

This is being implemented in OpenWSN. The next step is to evaluate the performance of the solution. We deployed the OpenTestbed at Inria-Paris (Fig. 5.1) specifically for that reason. We should be able to show that a single device running the same stack can satisfy both building-size and campus-size deployment, with the same industrial requirements.

7.3 (mid-term) Dependability, Determinism, Control loops

Today, the vast majority of TSCH activity (standardization, research, products) focuses on process *monitoring*: nodes are deployed to observe a process (industrial or not), and the network is designed to guarantee a very high level of end-to-end reliability. Given the scheduled nature of TSCH, there is a great potential for also offering latency "guarantees" and switch to process *control*. One can never guarantee a latency (wireless links are not perfect, so the tail of the latency distribution is in theory infinite), but one should be able to predict the latency distribution [195, 196].

Fig. 7.1 illustrates the first steps of that research, carried out with Craig Schindler [197]. On an inverted pendulum system, we connect the angle sensor with the car motor through a 3-hop OpenWSN network. The full-state controller is such that, if the network drops a packet, or if a packet has a latency above 150 ms (the critical delay), the rod falls over. As a very first proof-of-concept experiment, we show the stabilization of the system

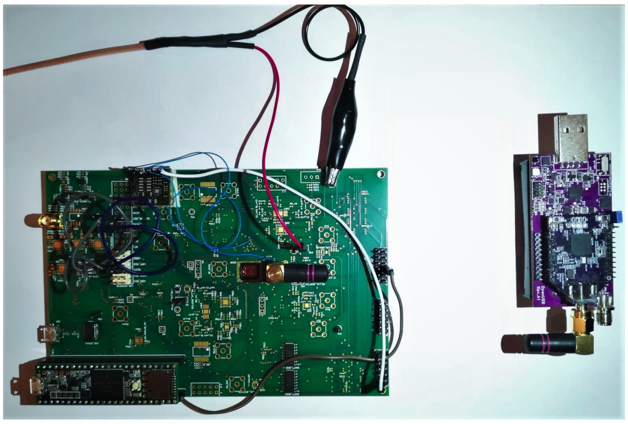


Figure 7.2: An early prototype of the single-chip mote mounted on a development board for easier debugging, next to an OpenMote.

by using a fully 6TiSCH-compliant implementation in which we hard-code a schedule.

The step after that is to design a tool which, given the connectivity graph and schedule of a network, can compute the latency distribution. This tool can then be used to compute the trade-off between latency and energy consumption. That is, answer questions such as: *if 99% of the traffic in a network gets to its destination in 100 ms, how much more energy will the nodes consume to bring that to 99.9%?* The ultimate goal of this research is to be able to install independent control loops between arbitrary source-destination pairs, possibly multiple hops away from one another, in a network that spans an entire factory floor.

7.4 (long-term) Smart Dust

The original "Smart Dust" project was a 1997 project[1], lead by UC Berkeley Prof. Pister, which aimed at creating a 1 mm^3 "mote" which embeds communication, computation and power. The 2001 final demo shows a 5 mm^2 MEMS corner cube optical transmitter wire-bonded to a CMOS ASIC. This project resonated with the academic community and contributed to starting the low-power wireless field.

With the technology having evolved, there is an opportunity to revisit this idea, and build a truly single-chip low-power wireless device. This is what the same UC Berkeley team has started working on [198, 199]; my team is involved with developing the software that goes onto that chip. Fig. 7.2 shows a picture of an early prototype of that single-chip mote.

One major research challenge with the single-chip mote is related to time

[1] `https://robotics.eecs.berkeley.edu/~pister/SmartDust/`

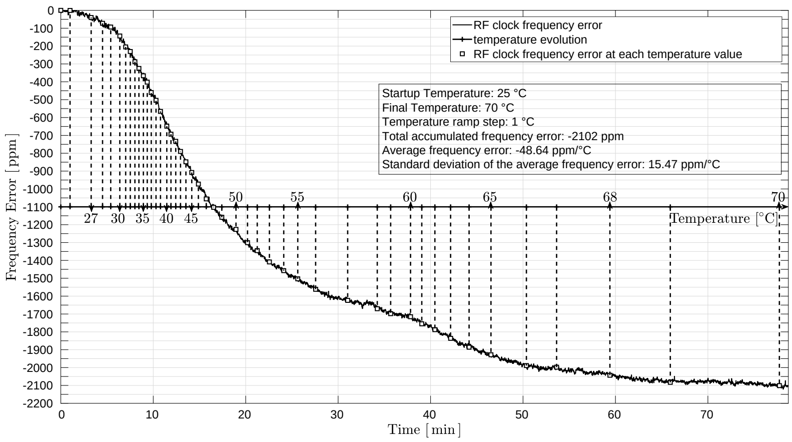


Figure 7.3: Clock frequency error when increasing the temperature from 25 C to 70 C.

keeping. Its single-chip nature prevents the use of an (external) crystal, neither for long time-scale timekeeping (typically done by a 32 kHz crystal), nor for frequency tuning (typically done by a fast 16-24 MHz crystal). Because the idea is to have a CMOS-only design to cut cost, MEMS-based oscillators are also not an option. Two options which are left are free-running LC-tank oscillators and ring oscillators. The challenge is that none of these clock sources are as stable as crystal oscillators, and that there is no on-board stable reference to tune against. Fig. 7.3 illustrates the problem by showing that these clock sources exhibit frequency errors over temperature in the 10's of thousands of ppm (where a typical crystal oscillator is in the 10-30 ppm range in the same conditions)

The idea is to use tune these clocks again two references: the frequency of an incoming RF signal, and the time measured between two periodic beacons. Early results are encouraging, as they show a free running LC tank has a frequency stability better than ± 40 ppm, the IEEE802.15.4 drift spec, in the absence of temperature changes [200]. And with an on-board temperature sensor, it should be possible to compensate for temperature changes. Similarly, the ring oscillator is shown to yield 99.8% packet receive, albeit with an FSK tone deviation double that of the IEEE802.15.4 specification [201].

Once the clock source challenge is overcome, numerous other fundamental research questions (on the firmware side) arise, including how to deal with different neighbors which each have a slightly different clock drift.

The availability of such Smart Dust would be revolutionary. Radios could be added to any components for little-to-no extra cost, rendering onboard buses (SPI, I2C, etc) obsolete. Smart Dust could be added in a cost-effective way to everyday objects which our phones could interrogate. The future wearable watch would not be a watch, but rice grain-sized device embedded in earrings. Interestingly, Smart Dust is at the Innovation Trigger stage of the 2017 Gartner Hype Cycle.

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A full list of my publications is available at `www.thomaswatteyne.com`.